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Soil Carbon, Nitrogen and Phosphorus Dynamics in Toposequences Adjacent to the Breton Plots, Alberta

by

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A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science

in

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The undersigned certify that they have read, and recommended to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled Soil Carbon, Nitrogen and Phosphorus Dynamics in Toposequences near the Breton Plots, Alberta submitted by Bei Zhu in partial fulfillment of the requirement for the degree of Master of Science in Soil Science.

ABSTRACT

This study was conducted on two toposequences located adjacent to the Breton Plots. The objectives were to quantify: (1) the distribution of soil types, soil organic matter and macro-organic matter, and the seasonal variation of soil water and temperature, available nutrients, crop production, and microbial biomass along toposequences; and (2) the dynamics of soil C, N and P under laboratory conditions. Field and laboratory studies showed that the quantity of soil organic matter, microbial biomass, and C and N mineralization increased from upper to lower slope positions in both fields, however the specific soil mineralization rates of C, N and ^{15}N, and the proportion of microbial biomass to total organic matter decreased from upper to lower slope positions. Therefore, factors controlling microbial activity (quantity of organic matter, moisture content, temperature, and nutrient availability) at different slope positions need to be considered in assessing organic matter dynamics in soils along toposequences.

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Chapter 1. Variability of Soil Properties across Toposequences

INTRODUCTION

Soils are dynamic, natural bodies in the landscape and evolve over time (Bridges 1997). The state of a soil or a soil property (s) in an undisturbed ecosystem can be described by a conceptual model proposed by Jenny (1941):

$$s = f(cl, o, r, p, t)$$

where cl is climate, o is organisms, r is topography, p is parent material, and t is age.

Soil variability naturally arises through complex interactions between climate, organisms, topography, parent material and time. Soil properties are dynamic at different time scales. For example, changes in total soil organic matter occur over decades or centuries. In contrast, changes in soil moisture and temperature occur during the diurnal cycle. Soil physical, chemical and biological properties also vary along a toposequence, and significantly influence the above- and below-ground plant productivity. Topography modifies both the microclimate and the hydrological conditions within a landscape. Therefore, it is important to quantify the variability of soil properties along a toposequence in order to understand fundamental ecosystem processes such as productivity, respiration, soil carbon sequestration, emission of greenhouse gases and microbial activity.

Topography influences soil formation primarily by its associated water and temperature relations. Water moves downhill and accumulates in soils of the depression areas more than in the higher areas. Therefore, soil water content is high in the depression areas. Such conditions can favor greater plant production and nutrient cycling in soils but slower decomposition of soil organic matter because of oxygen deficiency in saturated soils. This results in reduced soil organic matter oxidation and larger amounts of organic matter accumulation. Saturated condition also causes soils to be anaerobic in which the reduction of inorganic substances occurs. Gleying is typically found in the waterlogged soils as iron oxides are reduced.

Soils vary along a toposequence. A model toposequence for the Boreal forest of the Canadian Interior Plains shows Orthic Gray Luvisols in the upper and middle slope positions, Gleyed Gray Luvisols and Humic Luvic Gleysols in lower slope positions and Organic soils in depressions (Fig. 1.1). The hydrological cycle greatly influences the distribution of soils along the toposequence. Orthic Gray Luvisols are well to moderately well-drained and are found in the top and middle slope positions. In the lower slope position, water accumulates and soils are periodically saturated leading to the formation of Gleyed Gray Luvisols and Humic Luvic Gleysols. In the depressions, drainage is very poor and soils are subjected to prolonged periods of saturation, leading to the formation of Organic soils such as Fibric Mesisols. These areas also are discharge zones, where the water table comes close to the surface. This model toposequence shows that soils belonging to different orders are located within a small distance of one another.

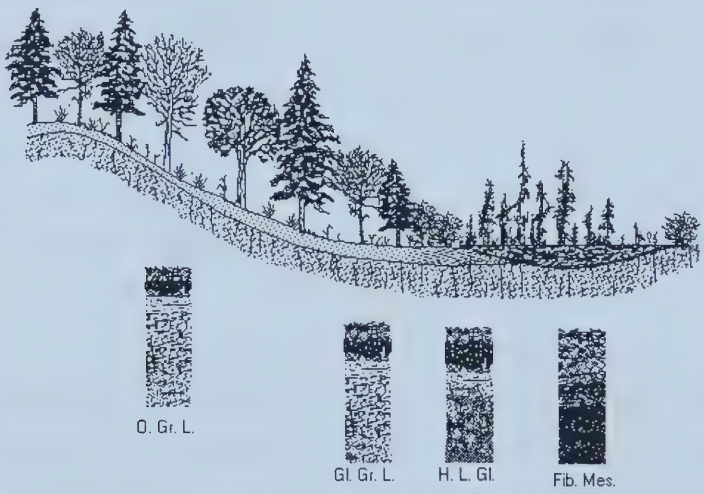

Fig. 1.1. Model topographic sequence in fine textured landscapes found in the Boreal forest of the Interior Plains (Martin and Juma 1997). (O.Gr.L. – Orthic Gray Luvisol; Gl.Gr.L. – Gleyed Gray Luvisol; H.L.Gl. – Humic Luvic Gleysol; Fib. Mes. – Fibric Mesisol).

Landscape dynamics and the associated variation in soil properties influence soil temperature and moisture regimes, transfer of water and nutrients, erosion, evapotranspiration, and crop production by Brubaker et al. (1994). They developed regression models to predict soil properties on different landscape positions from their observed values of soil organic matter, pH, exchangeable K, base saturation, available P

and K, and electrical conductivity. Landscape scale patterns of soil respiration and nitrification in forest soils were conducted under a mixed wood forest in Saskatchewan, Canada by Walley et al. (1995). They showed that topographically controlled hydrologic processes had a limited effect on C and N mineralization in these forest landscapes. The microscale variation in soil characteristics may have obscured detection of macroscale differences. Huang and Schoenau (1996) quantitatively assessed the soil C, N, P and S storage in the soil profiles along a catena under a typical old aspen forest of the southern Boreal region of Saskatchewan, Canada. The forms, amounts and distribution of soil C, N, P and were affected significantly by profile depth and slope positions. More than 95% of the C, N, P and S was in organic forms in the litter horizon at the study site. These studies were all performed in soils under forest vegetation and not in forest soil being used for crop and forage production.

The Breton plots of University of Alberta were established in 1930 to find "a system of farming suitable for the wooded soil belt". There are two long-term crop rotation studies consisting of a 2-yr wheat fallow rotation and a 5-yr wheat-oat-barley-forage-forage rotation at this site. In each rotation, there are several plots to test for the amendment of soil with fertilizers, manure and lime. Over the past 70 years, research on these plots has been conducted in the following areas: (1) overcoming nutrient deficiencies; (2) improving crop and soil quality; (3) addressing air and water quality; and (5) assessing local and global impacts. Crop yield and soil organic matter contents from different soil fertilizer treatments have been studied on these two cropping systems (Juma 1995). Generally the 5-yr rotation excels the 2-yr rotation in accumulation of soil organic matter, and the fertilized plots excel the control plots. The rotation effect is more distinct in 5-yr cropping system when a variety of crops were grown.

All the studies at the Breton Classical Plots have been conducted on plots, which have little or no slopes. This work was conducted on two fields adjacent to the Breton plots and provides information on the impact of topography on soil properties, water and temperature regimes, and C and N mineralization in the mix forage and the timothy fields. My study lies in the town of Breton, Alberta which is located 110 km southwest of Edmonton, Alberta (53° 05' N and 114° 27' W). The region belongs to the Low Boreal

ecoregion within the Boreal Plains ecozone. The dominant soils in the Breton area are Orthic Gray Luvisols and Dark Gray Luvisols in the upper and mid-slope positions. Most of the soils are being used for grain and forage production to support the livestock industry in this region.

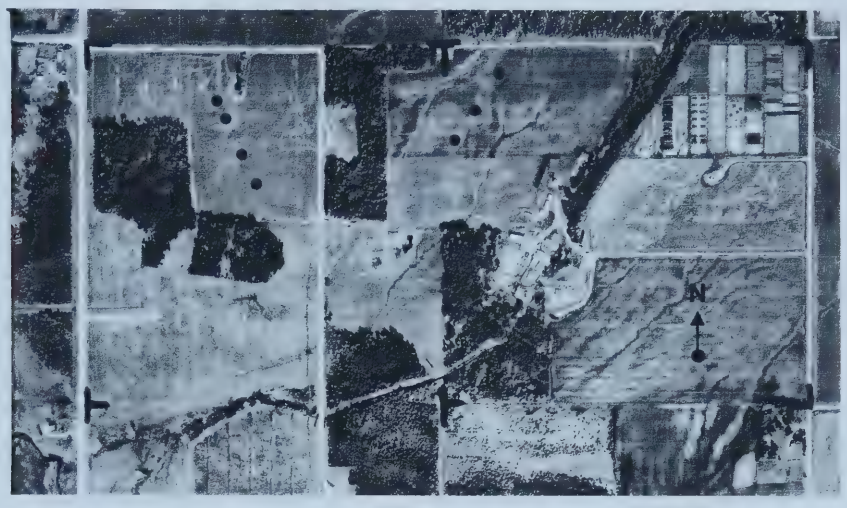

Fig. 1.2. An aerial view of Mr. Flesher's farm and the Breton plots.

The study sites were located on Mr. Bill Flesher's farm near Breton, Alberta (Fig. 1.2). The farm has four adjacent quarter sections of about 247 hectares. About 48% of the farm are organic soils, and 32% are the undulating to sloped upland with Luvisolic and Gleysolic soils. The toposequence chosen contained soils from Orthic Gray Luvisols on top slope positions, to Orthic Dark Gray Luvisols on mid slope positions, and Orthic Humic Gleysols on lower slope positions to Humic Eluviated Gleysols in depression areas. The two fields are adjacent to the Breton Classical Plots (located in the top right corner of the photograph). The two toposequences are shown with the marked dots in Fig. 1.2. Slopes of these fields ranged from 2-7%.

Mr. Flesher manages his fields to produce forage for pregnant mares. The mixed forage in the east field established in 1992 and consists of timothy (*Phleum pratense* L.) (50%), bromegrass (*Bromus inermis* Leyss.) (25%), alfalfa (*Medicago sativa* L.) (20%) and weeds (5%) according to Mr. Flesher's estimates The timothy in the west field is a

pure stand and was established in 1997. Both fields are fertilized annually. In 1997 and 1998, ammonium nitrate was uniformly applied at a rate of 84 kg N ha^{-1}.

The objectives of this study were to quantify: (1) the distribution of soil types, soil organic matter and macro-organic matter along toposequences; (2) seasonal variation of soil water and temperature, available nutrients, crop production, and microbial biomass along toposequences; (3) the soil C, N and P dynamics and the assessment of the quality of organic matter in soil samples from different slope positions by kinetic methods.

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Chapter 2. Total- and Macro- Organic Matter, and Mineralizable C and N in Soils Along Two Toposequences Near Breton, Alberta

INTRODUCTION

A model toposequence for the Boreal forest of the Canadian Interior Plains shows Orthic Gray Luvisols in the upper and middle slope positions, Gleyed Gray Luvisols and Humic Luvic Gleysols in lower slope positions, and Organic soils in depressions (Martin and Juma 1997). Therefore, crop production, nutrient use efficiency, and the storage of C, N, P and S in soil vary considerably along a toposequence. The forms, amounts and distribution of C, N, P and S in the soil profiles along a catena under a typical old aspen forest of the southern Boreal region of Saskatchewan, Canada were studied by Huang and Schoenau (1996). They found that the storage of organic N, P and S in the LFH and the mineral soils to 1 m depth increased by about 45, 24, and 46%, respectively, from the summit to lower slope positions. Soil organic matter generally increases from upper to lower slope positions in toposequences (Boehm and Anderson 1997; Honeycutt et al. 1990; Pierson and Mulla 1990).

Specific fractions of organic matter are responsive to management practices and are used as indicators of total soil organic matter changes (Gregorich et al. 1994; Bremer et al. 1994). Density fractionation separates soil organic matter into light and heavy fractions (Hassink 1995; Meijboom et al. 1995; Yakovchenko et al. 1998). Macroorganic matter (MOM) is a lighter fraction of organic matter that is > 250 μm in size (Theng et al. 1989), and is associated with sand-sized fraction. The MOM fraction is free of fine mineral particles and is not physical protected, therefore it decomposes more quickly (Sollins et al. 1984; Gregorich et al. 1989; Yakovchenko et al. 1998). The MOM fraction is more sensitive to changes in soil management and crop rotations than is total soil organic matter (Janzen et al. 1992; Skjemstad et al. 1988) or mineralized and microbial C and N (Biederbeck et al. 1994). In soil samples amended with MOM fraction, Yakovchenko et al. (1998) measured increases of 32% in biomass C and 46% in biomass N compared to the control soil. They suggested that the MOM fraction may be a suitable soil quality indicator.

Soil organic C, microbial biomass, and soil C and N mineralization were studied in three farming systems (crop-fallow, extended rotation, and continuous cropping) at a toposequence scale in the Dark Brown soil zone (mainly Dark Brown Chernozems) of Saskatchewan (Boehm and Anderson 1997). The average soil organic C content increased from the shoulder to the foot slopes in soils from all the cropping systems (about 25% by mass, 8% by volume). Increases in organic C (22% by mass, 3% by volume), microbial biomass (50%), and soil C and N mineralization (15% and 50%, respectively) were measured in continuously cropped compared to crop-fallow systems. Most of the studies on soil organic matter changes were conducted on different soil management systems. Information on the soil organic matter quality in toposequences in Gray Luvisols is needed.

The absolute amount of biomass at any one time cannot indicate whether soil organic matter is increasing or decreasing. The ratio of microbial biomass C to total C or the ratio of CO_2-C respired to microbial biomass C provides a measure of soil organic matter dynamics (Anderson and Domsch 1989; Anderson and Domsch 1990). The quality of soil organic matter may be distinguished by expressing mineralization data on an absolute and a relative basis (Rutherford and Juma, 1989a, b). Field studies were conducted on an Orthic Black Chernozem at the Ellerslie research station and on an Orthic Gray Luvisol at the Breton plots in Alberta. The total soil C at Ellerslie was 2.3 times higher than at Breton, and soil respiration during a 10-day incubation was 21% greater at Ellerslie than at Breton. However, when CO_2-C evolution was expressed as a proportion of soil C, the soil at Breton had 2.4 times respiration than that at Ellerslie. The amount of N mineralized over 40-week under laboratory conditions in the soil from Ellerslie was almost 3 times than that at Breton. However, the expression of mineral N as a proportion of total N showed that the N of the Breton soil was being mineralized at a higher rate than that in the Ellerslie (Rutherford and Juma, 1989a, b). The relative rate of C and N mineralization to total soil C and N will be used in assessing organic matter quality in our toposequences.

Most of the long-term studies in the University of Alberta Breton plots have concentrated on dynamics of crop yield and soil quality under different cropping systems.

Soil organic matter changes in toposequences with Gray Luvisols as dominant soils near the Breton Plots have not been studied. The objectives of this experiment were to: (1) identify soil types and quantify soil total C, N and P content along two toposequences; (2) compare the intensities of soil C and N mineralization in soils collected from different slope positions in a controlled laboratory environment.

MATERIALS AND METHODS

Sampling Methods

The experiment was conducted using a split plot design with the slope positions as main plot and soil depths as sub-plot on Mr. Bill Flesher's farm which lies 110 km south-west of Edmonton (53° 05'N and 114 27'W). A field with timothy grass and a field with mixed forages were chosen for the study. The landscapes were undulating to sloped upland. In the mixed forage field, five transects that cover upper, middle and lower slope positions were laid out in 1998. Because of the shape of the field, there were five replicates of sampling stations on the upper, four on the middle; and six on the lower positions, which gave a total of 15 sampling stations in the mixed forage field. In the timothy field, three transects that cover upper, middle, lower and toe slope positions were laid out at the same time. Three replicates of sampling stations per slope position were marked which gave a total of 12 sampling stations. The slopes were between 2-7%.

In fall 1998, soil samples were taken at each sampling station using a coring truck. The steel coring tube used was 50.8 cm long and 7.6 cm in diameter. Three cores were taken and were divided into 0-7.5, 7.5-15, 15-30 and 30-45 cm depths. The cores were composited and all soil samples were then air dried and weighed. Bulk density was calculated based on the dry soil mass and the volume of the soil in the coring tube. Soil samples were used to determine the total C, N and P contents. In 1999, soil profiles at each of the slope positions were described to a depth of 120 cm. All soils were classified according to Canadian System of Soil Classification. Soil texture was done by the hand texturing method.

Analytical Methods

Soil macro-organic matter (MOM) > 500 μm was separated from the air-dried soil using sieving/winnowing procedure (Ellert and Johnson 1997). The total C and N of the MOM fraction was done by Carlo Erba NA1500 nitrogen and carbon analyzer. Total P of the MOM fraction was done by Kjeldahl digestion. Soil pH was determined on a soil to water ratio of 1:2 by the Fisher Accumet pH meter model 630.

Air-dry soil samples from 0-7.5 and 7.5-15 cm depths, from which the MOM fraction was removed, were used in bioassay of mineralizable and soil microbial C and N experiment (Ellert and Johnson 1997). Air dried soil samples, 75-g equivalent oven-dry basis, were incubated at 80% field capacity moisture content at 22 °C for a total of 10 weeks in mason jars. Ten ml of 2 N NaOH was used for trapping the CO_2 evolved from the soil. Traps were changed on week 1, 4 and 10 and titrated with standardized HCl solutions. Both pre- and post- incubation air dried soils were extracted with 2 M KCl for total extractable mineral N. The net mineralizable N was calculated as the difference between pre- and post- incubation mineral N. The microbial biomass C was measured at the end of 10-wk incubation period by chloroform fumigation extraction method (Ellert and Johnson 1997).

The data were analyzed using a factorial split plot design consisting of three factors (field, slope position, soil depth) using the General Linear Models Procedure of SAS (Statistical Analysis System, SAS Institute Inc. 1990). All results are means of all replicates in a specific position. Duncan's Multiple Range Test procedure was used for multiple comparison of main factors. The Shapiro-Wilk statistic of the Univariate and Multivariate Normality Tests was used to test for data normality. Soil microbial biomass C was normalized with a natural log-transformation.

RESULTS

Soil characterization at the two studying fields

Pedon description

Pedon descriptions were conducted in the fields in Fall 1999. The profile horizonation, color and texture are described in Table 2.1. In the mixed forage field, soils

ranged from Orthic Dark Gray Chernozem to Gleyed Dark Gray Chernozem from upper to lower slope positions. In the timothy field, Orthic Dark Gray Chernozem was in the upper position, Dark Gray Luvisol was in the middle slope position, Gleyed Eluviated Black Chernozem in the lower and Orthic Humic Gleysol was in the toe slope position.

The previous Gray Luvisols in these fields were classified as Chernozems as the thickness and the color of the Ap horizon met the criteria of Chernozemic order. The increase of soil organic matter in the Ap horizon and the mixing of the Ae with Ap horizons was a result of agricultural activities leading to the change of Orthic Gray Luvisols to Dark Gray Chernozems. However, the two soil orders in these fields are very closely related. This shows how the human activity can change soils from one order to another.

Soil bulk density and pH, soil total C, N and P, soil C:N:P ratios in 0-7.5, 7.5-15, 15-30, and 30-45 cm depths

Soil bulk density did not differ significantly between two fields, but it was significantly different among slope positions and four soil depths (Table 2.2). There was a strong slope position and depth interaction. Generally, bulk density decreased from upper to toe slope position and increased from 0-7.5 to 30-45 cm depths. In the mixed forage field, the bulk density ranged from 1.0 – 1.1 Mg m^{-3} for the 0-7.5 cm soil and 1.1-1.2 Mg m^{-3} for the 7.5-15 cm soils from lower to upper slopes. There was no difference in bulk density among slope positions within the same soil depth, but deeper soil depth had significant higher bulk density than that of the shallower depth. In the timothy field, the bulk density ranged from 0.6 – 1.0 Mg m^{-3} for the 0-7.5 cm soils and 0.8-1.2 Mg m^{-3} for the 7.5-15 cm soils from toe to upper slopes. The upper and middle slopes had no difference, but the toe and lower slope positions were significantly different in bulk density in the timothy field.

Soil pH differed significantly among slope positions and soil depths (Table 2.2). There was no significant difference in pH between upper and middle slope positions. The soils of the upper and middle positions were more acidic than that of the lower and toe slope positions. Soil pH increased from upper to toe slope positions, and from 0-7.5 cm to 30-45 cm soil depths. There was no significant difference in pH between the 0-7.5

and the 7.5-15 cm soil depths and between the 15-30 and 30-45 cm soil depths. The 0-7.5 cm soil had the lowest pH, which was significantly different from that of the 30-45 cm soil depth.

The amount of total C in soils (Table 2.3) from the four depths showed no significant difference between two fields. However, total C was significantly different among different slope positions and soil depths. Generally total C content in soils increased along the toposequences. The average total C content in the 0-7.5, 7.5-15, and 15-30 cm soil depth (27,900, 29,000 and 32,000 kg ha^{-1}, respectively) was not significantly different. The 30-45 cm depth had significantly lower total C content than any of the upper three depths in all slope positions. In the mixed forage field, the total C content in the 0-7.5 cm depth ranged from 18,700 to 32,300 kg ha^{-1} from upper to lower slope position. The middle slope had 23,500 kg ha^{-1} of total C, which was not significantly different from that of the upper slope position. The total C in the lower slope position of the 0-7.5 cm depth had 53% more than that in the upper slope position. In the timothy field, the amount of total C ranged from 20,600 to 53,900 kg ha^{-1} from upper to toe slope position. There was no significant difference in total C content between the upper and middle slope positions. However the lower and toe slope had significantly higher total C contents, which were 30,200 and 53,900 kg ha^{-1} for the 0-7.5 cm, respectively. The soil total C in the toe slope position of the 0-7.5 cm depth had 89% more than that in the upper slope position.

Total N (Table 2.3) had similar trend to that of the total C in soils. There was no significant difference in total N contents between the two fields. There was a significant difference among slope positions and soil depths. Generally total N in soils increased from upper slope to toe slope positions. The 0-7.5 cm and 7.5-15 cm depths had no difference in total N content (2,280 and 2,380 kg ha^{-1} soil, respectively). But the 15-30 cm depth had significantly higher total N content (2,950 kg ha^{-1} soil). The 30-45 cm depth had significantly lower total N content (1,640 kg ha^{-1} soil). Total N content ranged from 1,710 to 2,650 kg ha^{-1} from upper to lower slope positions in 0-7.5 cm soil depth of the mixed forage field. There was no difference in total N between upper and middle slope positions; and the lower slope position had significantly higher total N. The total N

in the timothy field ranged from 1,780 to 3,760 kg ha^{-1} from upper to toe slope positions in the 0-7.5 cm soil depth. There was no significant difference in soil total N between upper, middle slope positions. The lower and toe slope positions had significantly higher amount of total N contents than that of the upper and middle slope positions. There was a significant difference between lower and toe slope positions in total N content.

Total P (Table 2.3) in soils was not significantly different between two fields, but was different among slope positions and soil depths. The 0-7.5 and 7.5-15 cm depths had similar total P content; the 15-30 and 30-45 cm depths had significantly higher total P contents than the upper two depths. In the mixed forage field, there was no significant difference among the three slope positions, which ranged from 482 to 513 kg ha^{-1} soil. In the timothy field the toe slope had a total P content of 583 kg ha^{-1} soil in the 0-7.5 depth, which was significantly higher than other slope positions. The lower slope position of the field had 432 kg ha^{-1} soil in the 0-7.5 depth, which was the lowest spot in total P content. However, there was no significant difference in total P content among upper, middle and lower slope positions.

Soil total C:N, total C:P and total N:P ratios were not significantly different between two fields, but significantly different among slope positions and soil depths (Table 2.4). The soil total C:N, total C:P and total N:P ratios generally increased from upper to toe slope positions but decreased from 0-7.5 cm to 30-45 cm depths. All ratios were not significantly different between 0-7.5 to 7.5-15 cm depths. However, all ratios decreased significantly in the 15-30 cm depth followed by the 30-45 cm depths.

Macro-organic matter (MOM) fraction

The MOM fraction was expressed as a percentage of the total dry soil weight (Table 2.5). There was no significant difference in the amount of MOM fraction between two fields, but there was significant difference in MOM fraction among different slope positions and between the two soil depths. There was a strong interaction between field and soil depth. In the mixed forage field, the upper slope had the lowest MOM fraction (0.54%), which was significantly different from middle and lower slope positions (0.78% and 0.84%, respectively) in the 0-7.5 cm soil. There was no significant difference

between middle and lower slope positions. The 7.5-15 cm soil had much lower MOM fraction, with upper and middle slopes being the same (0.10%) and the lower slope position had significantly higher amount of MOM fraction (0.17%). In the timothy field, the upper and middle slopes of 0-7.5 cm soil showed no significant difference in MOM fraction (0.41% and 0.47%, respectively). The lower and toe slope positions were not different from each other (0.74% and 0.76%, respectively) but they were significantly higher than the upper and middle slope positions. However, in the 7.5-15 cm soil, only the lower slope position had the highest amount of MOM fraction (0.30%), the rest of the slope positions were not significantly different from each other.

Total C content (Table 2.5) in the MOM fraction was significantly different between two fields, two soil depths and among slope positions. There was a strong field and depth interaction. The mixed forage field (1,240 kg ha^{-1} soil by overall average) had about 1.5 times more MOM total C than the timothy field (860 kg ha^{-1} soil by overall average). In the 0-7.5 cm soil depth, the MOM total C (1,740 kg ha^{-1} soil) was four times greater than that in the 7.5-15 cm soil (410 kg ha^{-1} soil). In the mixed forage field the MOM total C in 0-7.5 cm soil ranged from 1,620 to 2,340 kg ha^{-1} soil. The upper slope had significantly lower MOM total C than middle and lower slope positions. There was no difference between middle and lower slopes. In the timothy field the MOM total C in 0-7.5 cm soil ranged from 1,080 to 1,530 kg ha^{-1} soil for different slope positions. There was no significant difference among upper, middle and toe slope positions. The lower slope position had significantly higher MOM total C content in both soil depths than that of the other slope positions (1,530 and 770 kg ha^{-1} soil for 0-7.5 and 7.5-15 cm depths, respectively).

Total N content (Table 2.5) in the MOM fraction showed no differences between two fields and among different slope positions. However there was a significant difference between two soil depths. The 0-7.5 cm soil depth (54.4 kg ha^{-1} soil) had higher MOM total N than the 7.5-15 cm depth (13.1 kg ha^{-1} soil). The MOM total N ranged from 39.4 to 69.9 kg ha^{-1} soil for different slope positions in the 0-7.5 cm soils and it ranged from 9.0 to 22.8 kg ha^{-1} soil for different slope positions in the 7.5-15 cm soils. The middle slope position of the mixed forage field and the lower slope position of the timothy field

had the higher total amount of MOM total N in the two soil depths. The toe slope position had the lowest amount of MOM total N in both soil depths this time.

Total P content (Table 2.5) of the MOM fraction was not significantly different between two fields, but there was a significant difference among slope positions and between two soil depths. There was a field and depth interaction, which means that the change of MOM total P in the two soil depths was not the same for the two fields. The 0-7.5 cm soils (17.0 kg ha^{-1} soil) had significantly higher amount of MOM total P than the 7.5-15 cm soils (4.2 kg ha^{-1} soil). In the mixed forage field there was a significant difference in MOM total P among slope positions in both depths (from 13.8 to 23.8 kg ha^{-1} soil in 0-7.5 cm; and 2.3 to 5.4 kg ha^{-1} soil in 7.5-15 cm). But the lower slope position had significantly higher amount of MOM total P (23.8 and 5.4 kg ha^{-1} soil in the 0-7.5 and 7.5-15 cm, respectively). In the timothy field there was no significant difference among different slope positions in 0-7.5 cm depth, but the lower slope had higher MOM total P in 7.5-15 cm depth. The lower slope position tended to have higher amount in MOM total P in both fields and both soil depths.

MOM fraction total C:N, total C:P and total N:P ratios were significantly different between two fields and among slope positions (Table 2.6). These ratios were not significantly different between the two soil depths. There was a field and depth interaction in the MOM fraction C:N and N:P ratios; a field and slope position interaction in the MOM fraction C:P and N:P ratios. The MOM fraction C:N ratio increased from upper to toe slope positions. The MOM fraction C:P and N:P ratios were significantly lower in the toe slope positions.

The 10-wk laboratory incubation study

SOIL MICROBIAL BIOMASS C AND MICROBIAL ACTIVITY: In the 10-wk incubation, there was no significant difference in soil microbial biomass C between two fields, but there was significant difference among slope positions. Microbial C in the 7.5-15 cm soil had higher amount of biomass C than that of the 0-7.5 cm depth. Soil microbial biomass C increased along the slope positions (Fig. 2.1 a). The mixed forage field had different microbial C among all slope positions, with the lowest occurring in the

upper and highest in the lower slope position (283 and 428 kg ha^{-1} in 0-7.5 cm depth, respectively). In the timothy field, there was no significant difference in biomass C between upper and middle slope positions (243 and 232 kg ha^{-1} in 0-7.5 cm depth, respectively). The lower and toe slope positions had significantly higher biomass C (217 and 306 kg ha^{-1} in 0-7.5 cm, respectively). The toe slope position had the highest amount of biomass C.

The proportion of microbial biomass was expressed as a percentage of the total soil C content. An opposite trend to the absolute biomass C was observed (Fig. 2.1 b). There was no significant difference in the proportion of microbial biomass between two fields but there was significant difference between the two soil depths and among slope positions. The proportion of microbial biomass was higher in the 7.5-15 cm soil than in the 0-7.5 cm soil. The proportion of microbial biomass decreased from upper to lower slope positions in both fields. In the mixed forage field, the upper and middle slopes had no significant difference in the proportion of microbial biomass, and they were significantly higher than the lower slope position. In the timothy field, there was no significant difference between upper and middle slope position, and between lower and toe slope position. The lower and toe slope positions had significantly lower proportions of microbial biomass.

CUMULATIVE CO_2-C AND PROPORTION OF TOTAL C RESPIRED: Soil respiration during the 10-wk incubation period showed that the cumulative respiration increased over time for all depths in soil samples from both fields (Fig. 2.2). The trend of CO_2-C respiration among slope positions was consistent for the 7, 28, and 70-day incubation periods. There was no significant difference in cumulative soil respiration in the upper and middle slope positions. The highest amount occurred in the toe slope position of the timothy field. CO_2-C evolved from the 0-7.5 cm soil depth was greater than that from the 7.5-15 cm soil depths. There was no significant difference in soil respiration between two fields. However, when the soil respiration was expressed as a proportion of total C (amount of CO_2-C evolved divided by the total C content), an opposite trend was found. The highest proportion of soil respiration occurred in the

upper and middle slope positions. The lowest occurred in the toe slope positions. The proportion of total C mineralized also decreased during the incubation period (Fig. 2.3).

NET MINERALIZABLE N AND PROPORTION OF TOTAL N MINERALIZED: Net mineralizable N from two fields did not differ significantly (Fig. 2.4 a and b), but there was a significant difference among slope positions, and between 0-7.5 cm and 7.5-15 cm soils. In the mixed forage field, there was no significant difference in net mineralizable N between upper and middle slope positions at both depths, but there was a significantly higher amount of net mineralizable N in the lower slope position. In the timothy field, the toe slope position had the highest amount of net mineralizable N followed by that in the lower slope position. The upper and middle slopes had no significant difference in the amount of net mineralizable N. In both fields, mineralizable N in the 0-7.5 cm depth was significantly higher than in the 7.5-15 cm depth. The percentage of N mineralization (net N mineralized during 70 days/total N) yielded similar trend as the proportion of soil respiration in both soil depths and both fields (Fig. 2.4 a and b). The highest specific N mineralization occurred in the upper and middle slope positions. There was no difference in the upper and middle slope positions in specific N mineralization. The lowest specific N mineralization occurred in the toe slope position of the timothy field. Specific N mineralization in the 0-7.5 cm was greater than that in the 7.5-15 cm depth.

DISCUSSION

Assessment of Quality of Organic Matter Using a Kinetic Approach

Soil organic matter comprises a wide range of humified and biologically active compounds, including readily decomposable material, plant litter and roots, and dead and living organisms. The chemically well-defined non-humic substances that contribute to the organic C and N contents in soil consist of low molecular weight aliphatic and aromatic acids, carbohydrates, amino acids, and their polymeric derivatives (Schnitzer 1991). These compounds have a relatively rapid turnover in soil and are readily used as substrates by soil microorganisms. Humic substances make up a significant portion of soil organic C and N. They consist of complex polymeric organic compounds with high molecular weight and are intimately associated with soil inorganic constituents. The complex chemical structures make them more resistant to decomposition than the non-

humic materials. In the mixed forage field, the soil at the lower slope position was a Gleyed Dark Gray Chernozem compared to the Orthic Dark Gray Chernozems in the upper and middle slope positions. In the timothy field, the sequence of soils from the upper, middle, low, and toe slope positions was Orthic Dark Gray Chernozem, Dark Gray Luvisol, Gleyed Eluviated Black Chernozem, and Orthic Humic Gleysol (Table 2.1). The soils at the lower slope positions had restricted drainage compared with the upper slope positions. Soils that undergo periodic or sustained reducing conditions and low mean temperature may have an anaerobic conditions that result in the preservation of SOM relative to the better drained higher landscape elements (Baldock and Nelson 2000; Stevenson 1994). Novak and Bertsch (1991) compared the chemical characteristics of humic substances in forested soils from upland and bottomland in Coastal Plain of South Carolina. They found higher organic C content, O-alkyl structured compounds, humic acids and HA/FA ratios in the bottomland soils. They suggested that topography might modify the formation and nature of humic substances in SOM by influencing the drainage, vegetation and litter quality. Rapid C efflux from the upland soils would reduce the residence time of humic acid precursors and leaching of those compounds to the bottomland soils may favor the formation of higher amount of humic substances. Soils of lower slope positions in our study sites may contain higher amount of resistant humic materials than the upper position. Therefore, lower mineralization rates relative to total soil organic matter may occur in those soils.

In the 10-wk incubation experiment, the absolute amount of microbial biomass, soil C respiration, and net N mineralization increased from the upper to toe slope positions (Fig. 2.1a, Fig. 2.2, Fig. 2.4 a) and is correlated to the soil organic matter content (r^2 = 0.62*, 0.65* and 0.59*, respectively). These results are similar to those found in other toposequence scale studies in arable soils. For example, Sutherland et al. (1993) detected highest total soil respiration from depressions in an agricultural landscape with a slope of 2-5%. Schimel et al. (1985) measured highest laboratory and in-situ N mineralization rates in footslope position followed by the summit positions in a soil catena of shortgrass steppe in Colorado.

The specific C mineralization rates calculated in the 7, 28 and 70 day incubation studies significantly decreased in all soil samples from both of the fields. The highest mineralization rate occurred in the first week. This suggests that readily decomposable substrates were utilized first followed by resistant substrates. Blet-Charaudeau et al. (1990), Bonde and Lindberg (1988), and Robertson et al. (1988) all reported that the rates of C and N mineralization were greater during the first 10 days of 12 to 26 wk laboratory incubations.

The absolute amounts of microbial biomass C and CO_2-C respiration were all higher in the lower slope positions. In contrast, the percentages of microbial C to total soil C, and respired C to total C all decreased from upper to lower slope positions. The CO_2 metabolic quotient (qCO_2, which is CO_2-C evolved/microbial C) decreased from upper to lower slope positions correspondingly. The availability of substrates controls the size and activity of microbial biomass. The kinetic data showed that substrates in the upper slope positions were more readily available to microbes than those in the lower positions. The lower slope positions had more resistant organic matter, which supported a proportionally lower and less active biomass. Anderson and Domsch (1993) used the qCO_2 as an indicator of the physiological state of microbial communities. In studies of stability criteria of forest ecosystems, they found that a high qCO_2 at low soil pH indicated stress on microbes. They also suggested the decreased qCO_2 was accompanied by increased ecosystem maturity.

Although the lower and toe slope positions had the highest absolute C and N mineralization rates, the percentage of total C and N mineralized (quantity of C or N mineralized as a percentage of total organic C or N over specified time intervals) showed an inverse trend. As the incubation experiment was conducted under controlled temperature and moisture conditions, the specific mineralization rates may be used as an indicator of the quality of soil organic matter at different slope positions. The specific mineralization rates for soils from different slope positions were significantly different, therefore the quantity as well as quality of organic matter, and the size and activity of microbial biomass, need to be considered in the calculation of flux measurements from different positions in a toposequence.

Assessment of Quality of Organic Matter Using the MOM fraction and Total Soil C, N and P

Soil total C, N and P and MOM fraction measured in Fall 1998 increased from upper to lower slope positions (Table 2.3 and 2.5). The higher SOM contents in the lower slope positions may be due to the kinetics of soil mineralization discussed above, soil water and temperature, which occur in the toposequences. The lower slope positions had higher moisture content and lower soil temperature than the upper slope positions. Higher moisture content supported greater above ground plant productions (Refer to Chapter 3). Stevenson and Kessel (1997) and Schimel et al. (1985) also found higher plant yields in the footslope positions. Higher above ground plant production is correlated to a higher production of root biomass and C input into soil (Zasada et al. 1994; Haugen-Kozyra et al. 1993). Soil organic matter was mineralized at a slower relative rate in the lower slope positions. Under cool and wet conditions, decomposition is confined to anaerobic processes and organic matter may continue to increase because the rate of mineralization is reduced. Greater SOM content in the lower slope positions in our study sites may be due to higher C input rates and lower output rates relative to input rates over decades and centuries.

The quality of organic matter was different in soils along the slope positions. The percentage of total soil C and N mineralized during the 10-wk incubation showed a decreasing trend from upper to lower slope positions. Schimel et al. (1985) and Raghubanshi (1992) also found a decreasing trend of relative OM mineralization down the slope in soil catenas. The N and P nutrient availability from different slope positions showed that the lower positions tended to have lower inorganic N and P contents than the upper and middle slopes in fields (Refer to Chapter 3). The limitation of available nutrients could result in unfavorable conditions for soil decomposer microbial community, which would lead to a slower rate of soil microbial production. The soil and MOM fraction total C:N ratio increased from upper to lower slope positions of the toposequences. Wider C/N ratios indicate less substrate availability for decomposers than do narrower ratios, which may also explain the lower relative rate of soil mineralization in the lower slope positions. This increase of C/N ratio along the toposequences may also indicate the higher C inputs to the system. The N could be

immobilized by plant uptakes, which led to less organic matter mineralization in those slope positions. The MOM fraction total C:P and N:P ratios decreased from upper to lower slope positions indicating higher amount of organic form P in soils of the lower slope positions.

Implications

The intensity of soil forming processes varies along a toposequence and results in a differences of pool sizes and flux between the pools. In this study, significant differences in the C, N, and P content of total- and macro- organic matter were measured. The dynamics of organic matter were measured under laboratory conditions. Moisture and temperature regimes vary along a toposequence and control plant production and biological activity in soil. Therefore, it is necessary to study these processes under field conditions. This issue is addressed in the next chapter.

Table 2.1. Soil profiles for the mixed forage and the timothy fields at Breton (According to the Canadian System of Soil Classification).

Soil	Slope position	Depth (cm)	Genetic horizon	Color (moist)	Texture
		Mixed forage field			
Orthic Dark Gray Chernozem	Upper	0-20	Ap	10YR 3/2	Loam
		20-40	Bt_1	10YR 4/3	Clay loam
		40-90	Bt_2	10YR 4/3	Clay loam
		90-120	BC	10YR 4/1	Clay loam
Orthic Dark Gray Chernozem	Middle	0-20	Ap	10YR 3/2	Loam
		20-50	Bt_1	10YR 3/3	Clay loam
		50-100	Bt_2	10YR 4/3	Clay loam
		100-120	BC	10YR 5/3	Clay loam
Gleyed Dark Gray Chernozem	Lower	0-20	Ap	10YR 3/1	Loam
		20-40	Bt_1	10YR 3/2	Clay loam
		40-65	Bt_2	10YR 4/1	Clay loam
		65-110	Btg	10YR 4/1	Clay loam
		110-120	BCg	10YR 5/1	Clay loam
		Timothy field			
Orthic Dark Gray Chernozem	Upper	0-17	Ap	10YR 3/2	Loam
		17-33	Bt_1	10YR 4/3	Clay loam
		33-51	Bt_2	10YR 4/3	Clay loam
		51-92	Bt_3	10YR 3/3	Clay loam
		92-120	BC	10YR 5/3	Clay loam
Dark Gray Luvisol	Middle	0-17	Ap	10YR 3/3	Loam
		17-28	Ahe	10YR 3/2	Silt loam
		28-33	Ae	10YR 4/3	Silt loam
		33-65	Bt_1	10YR 4/1	Clay loam
		65-100	Bt_2	10YR 4/1	Clay loam
		100-114	BC	10YR 5/4	Clay loam
		114-120	Ck	2.5YR 5/4	Clay loam
Gleyed Eluviated Black Chernozem	Lower	0-20	Ap	10YR 2/1	Loam
		20-40	Ahe	10YR 3/1	Clay loam
		40-63	Bgj	10YR 4/2	Clay loam
		65-80	Bg_1	10YR 5/3	Clay loam
		80-100	Bg_2	10YR 5/4	Clay loam
		100-120	Cg	10YR 5/2	Clay loam
Orthic Humic Gleysol	Toe	0-16	Ap	10YR 2/2	Loam
		16-30	Aheg	10YR 4/1	Clay loam
		30-60	Bg	10YR 5/2	Clay loam
		60-120	BCg	10YR 5/3	Clay loam

Table 2.2. Soil bulk density and pH in four depths from different slope positions in the mixed forage and timothy fields.

Slope position	Soil Depth			
	0-7.5 cm	7.5-15 cm	15-30 cm	30-45 cm
	Bulk Density (Mg m^{-3})			
	Mixed forage field			
Upper	1.1 a	1.2 b	1.3 g	1.4 h
Middle	1.1 a	1.2 b	1.3 g	1.4 h
Lower	1.0 a	1.1 b	1.3 g	1.4 h
	Timothy field			
Upper	1.0 a	1.2 b	1.3 g	1.4 h
Middle	1.1 a	1.3 b	1.2 g	1.4 h
Lower	0.8 c	1.0 e	1.2 g	1.3 h
Toe	0.6 d	0.8 f	1.3 g	1.3 h
	pH (1 : 2 soil to water ratio)			
	Mixed forage field			
Upper	5.6 a	5.7 ad	5.8 d	6.0 d
Middle	5.7 a	5.7 ad	5.8 d	6.0 d
Lower	6.2 b	6.3 be	6.3 e	6.5 e
	Timothy field			
Upper	5.8 a	5.8 ad	5.9 d	6.0 d
Middle	5.7 a	5.9 ad	6.0 d	6.1 d
Lower	5.9 b	6.2 b	6.7 e	6.8 e
Toe	7.0 c	7.1 cf	7.2 f	7.2 f

Summary of ANOVA

Source of variation	d.f.	Bulk Density	pH
Field	1	NS	NS
Position	3	***	***
Field × Position	3	NS	NS
Depth	1	***	**
Field × Depth	1	NS	NS
Position × Depth	3	***	NS
Field x Position x Depth	3	NS	NS

For each row and column, values of each variable marked with the same letter are not significantly different ($P<0.05$); LSD: bulk density = 0.06; pH = 0.24

*, **, *** $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively; NS, not significant.

Table 2.3. Total C, N and P contents in soils at four depths from different slope positions in the mixed forage and timothy fields.

Slope Position	Soil Depth			
	0-7.5 cm	7.5-15 cm	15-30 cm	30-45 cm
		Total C (kg ha^{-1})		
		Mixed forage field		
Upper	18 700 a	18 800 a	25 500 a	15 200 d
Middle	23 500 a	21 600 a	30 700 a	20 900 d
Lower	32 300 b	31 800 b	38 200 b	13 900 e
		Timothy field		
Upper	20 600 a	20 300 a	16 600 a	9 200 d
Middle	19 400 a	21 900 a	30 700 a	11 900 d
Lower	30 200 b	36 000 b	43 700 b	19 700 e
Toe	53 900 c	58 000 c	40 200 c	10 900 f
		Total N (kg ha^{-1})		
		Mix forage field		
Upper	1 710 a	1 760 a	2 540 c	1 690 e
Middle	2 040 a	1 950 a	2 920 c	2 120 e
Lower	2 650 b	2 650 b	3 400 d	1 630 f
		Timothy field		
Upper	1 780 a	1 780 a	1 820 c	1 180 e
Middle	1 730 a	1 950 a	2 860 c	1 490 e
Lower	2 360 b	2 840 b	3 840 d	1 930 f
Toe	3 760 b	4 030 b	3 150 d	1 310 f
		Total P (kg ha^{-1})		
		Mixed forage field		
Upper	513 a	543 a	988 c	905 c
Middle	482 a	470 a	821 c	745 c
Lower	488 a	480 a	910 c	853 c
		Timothy field		
Upper	546 a	585 a	1 070 c	1 012 c
Middle	515 a	550 a	1 010 c	911 c
Lower	432 a	477 a	936 c	812 c
Toe	583 b	684 b	1 370 d	1 383 d

Summary of ANOVA

Source of variation	d.f.	Total C	Total N	Total P
Field	1	NS	NS	NS
Position	3	***	***	***
Field × Position	3	NS	NS	NS
Depth	3	***	***	***
Field × Depth	3	NS	NS	NS
Position × Depth	9	NS	NS	NS
Field × Position × Depth	9	NS	NS	NS

For each row and column, values of each variable marked with the same letter are not significantly different ($P<0.05$); LSD: Total C = 7000; Total N = 497; Total P = 95

*, **, *** $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively; NS, not significant.

Table 2.4. Total C:N, total C:P, total N:P ratios in soils at four depths from different slope positions in the mixed forage and timothy fields.

Slope Position	Soil Depth			
	0-7.5 cm	7.5-15 cm	15-30 cm	30-45 cm
		Total C:N		
		Mixed forage field		
Upper	11 a	11 a	10 d	8 f
Middle	12 a	11 a	10 d	9 f
Lower	12 a	12 a	11 d	8 f
		Timothy field		
Upper	12 a	11 a	9 d	8 f
Middle	11 a	11 a	11 d	8 f
Lower	13 b	13 b	11 d	10 g
Toe	14 c	14 c	13 e	8 f
		Total C:P		
		Mixed forage field		
Upper	36 a	34 a	26 e	16 g
Middle	49 b	46 b	36 f	26 h
Lower	67 c	68 c	40 f	17 g
		Timothy field		
Upper	39 a	36 a	16 e	10 g
Middle	37 a	40 a	31 f	13 g
Lower	70 c	77 c	45 f	24 h
Toe	93 d	85 d	30 f	8 g
		Total N:P		
		Mixed forage field		
Upper	3.3 a	3.2 a	2.6 c	1.8 e
Middle	4.2 b	4.2 b	3.5 d	2.7 f
Lower	5.5 b	5.7 b	3.6 d	1.9 e
		Timothy field		
Upper	3.3 a	3.2 a	1.7 c	1.2 e
Middle	3.4 a	3.5 a	2.9 c	1.6 e
Lower	5.5 b	5.9 b	4.0 d	2.3 f
Toe	6.5 b	5.9 b	2.3 c	1.0 e

Summary of ANOVA

Source of variation	d.f.	C:N	C:P	N:P
Field	1	NS	NS	NS
Position	3	***	***	***
Field × Position	3	NS	NS	*
Depth	3	***	***	***
Field × Depth	3	NS	NS	NS
Position × Depth	9	NS	***	***
Field × Position × Depth	9	NS	NS	NS

For each row and column, values of each variable marked with the same letter are not significantly different ($P<0.05$).

*, **, *** $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively; NS, not significant.

Table 2.5. Total C, N and P contents in the MOM (Macro-organic Matter) fraction of soils at two depths from different slope positions in the mixed forage and timothy fields.

Slope Position	MOM fraction (%)		Total C (kg ha^{-1})		Total N (kg ha^{-1})		Total P (kg ha^{-1})	
	0-7.5 cm	7.5-15 cm	0-7.5 cm	7.5-15 cm	0-7.5 cm	7.5-15 cm	0-7.5 cm	7.5-15 cm
Mixed forage field								
Upper	0.54 a	0.10 c	1 620 a	312 e	54.1 a	10.5 c	13.8 a	2.3 c
Middle	0.78 b	0.10 c	2 330 b	285 e	69.9 a	10.5 c	18.0 a	2.0 c
Lower	0.84 b	0.17 c	2 340 b	492 e	58.0 a	15.4 c	23.8 b	5.4 d
Timothy field								
Upper	0.41 a	0.12 c	1 080 c	343 e	46.1 a	12.4 c	11.8 a	4.7 a
Middle	0.47 a	0.12 c	1 280 c	346 e	47.8 a	11.5 c	14.7 a	4.4 a
Lower	0.74 b	0.30 d	1 530 d	765 f	57.7 b	22.8 c	17.6 a	8.0 d
Toe	0.76 b	0.15 c	1 240 c	314 e	39.4 a	9.0 d	14.6 a	3.6 a

Summary of ANOVA

Source of variation	d.f.	MOM fraction	Total C	Total N	Total P
Field	1	NS	***	NS	NS
Position	3	***	***	NS	***
Field × Position	3	NS	NS	NS	NS
Depth	1	***	***	***	***
Field × Depth	1	**	***	NS	**
Position × Depth	3	NS	NS	NS	NS
Field × Position × Depth	3	NS	NS	NS	NS

For each row and column, values of each variable marked with the same letter are not significantly different ($P<0.05$); LSD: MOM fraction = 0.13; Total C = 308; Total N = 10.4; Total P = 3.3

*, **, *** $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively; NS, not significant.

Table 2.6. Total C:N, total C:P and total N:P ratios in the MOM (Macro-organic Matter) fraction of soils at two depths from different slope positions in the mixed forage and timothy fields.

Slope Position	Soil Depth	
	0-7.5 cm	7.5-15 cm
	MOM Total C:N	
	Mixed forage field	
Upper	31 a	31 e
Middle	34 a	27 e
Lower	41 b	34 f
	Timothy field	
Upper	24 c	28 g
Middle	26 c	30 g
Lower	26 cd	33 gh
Toe	31 d	35 h
	MOM Total C:P	
	Mixed forage field	
Upper	121 a	132 a
Middle	131 a	141 a
Lower	99 b	94 b
	Timothy field	
Upper	92 c	73 d
Middle	88 d	78 d
Lower	87 d	94 c
Toe	85 d	88 d
	MOM Total N:P	
	Mixed forage field	
Upper	4.0 a	4.5 c
Middle	4.0 a	5.2 c
Lower	2.4 b	2.9 d
	Timothy field	
Upper	3.9 a	2.6 e
Middle	3.5 a	2.6 e
Lower	3.3 a	2.9 e
Toe	2.7 b	2.5 e

Summary of ANOVA

Source of variation	d.f.	C:N	C:P	N:P
Field	1	**	***	**
Position	3	**	**	***
Field × Position	3	NS	***	***
Depth	1	NS	NS	NS
Field × Depth	1	**	NS	***
Position × Depth	3	NS	NS	NS
Field × Position × Depth	3	NS	NS	NS

For each row and column, values of each variable marked with the same letter are not significantly different ($P<0.05$).

*, **, *** $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively; NS, not significant.

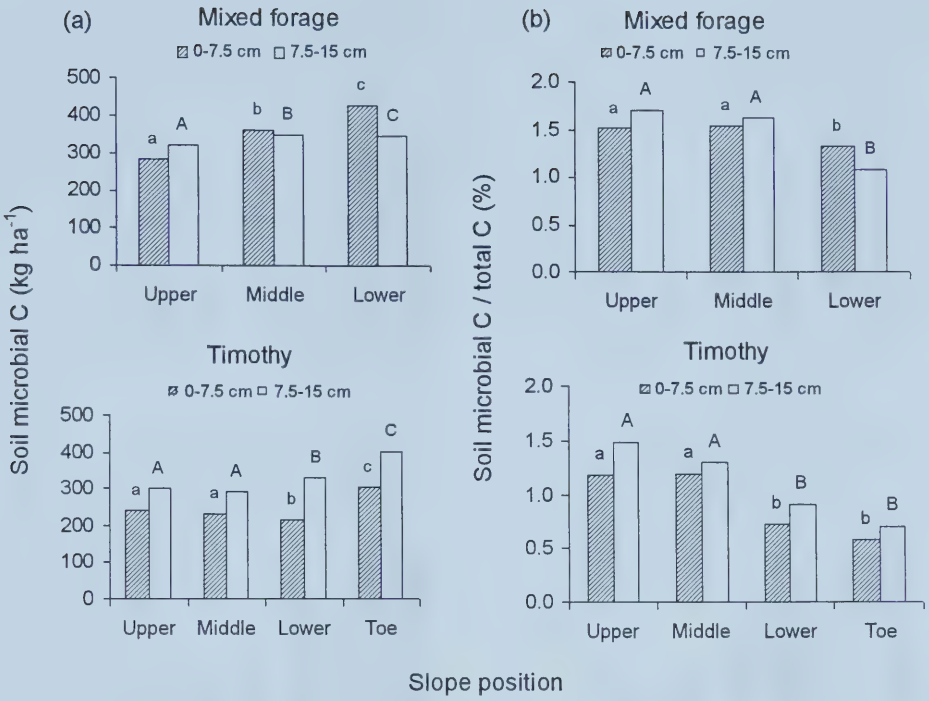

Fig. 2.1. Soil microbial biomass C (a) and soil biomass C as a proportion of total C (b) in soil samples used in the 10-wk incubation experiment; LSD: Microbial C = 44; Microbial C/total C = 0.17. Bars carrying the same letter are not significantly different ($P < 0.05$).

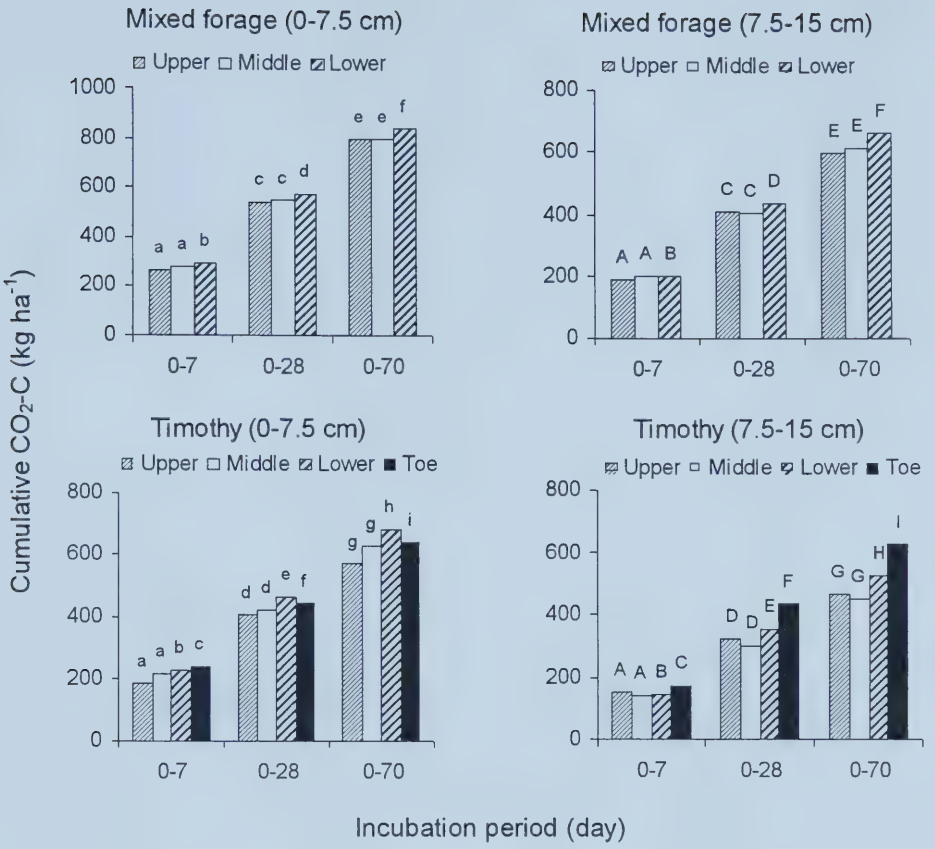

Fig. 2.2. Cumulative CO_2 evolved from soil samples taken from two fields during 10-wk incubation; LSD = 78. Bars carrying the same letter are not significantly different ($P < 0.05$).

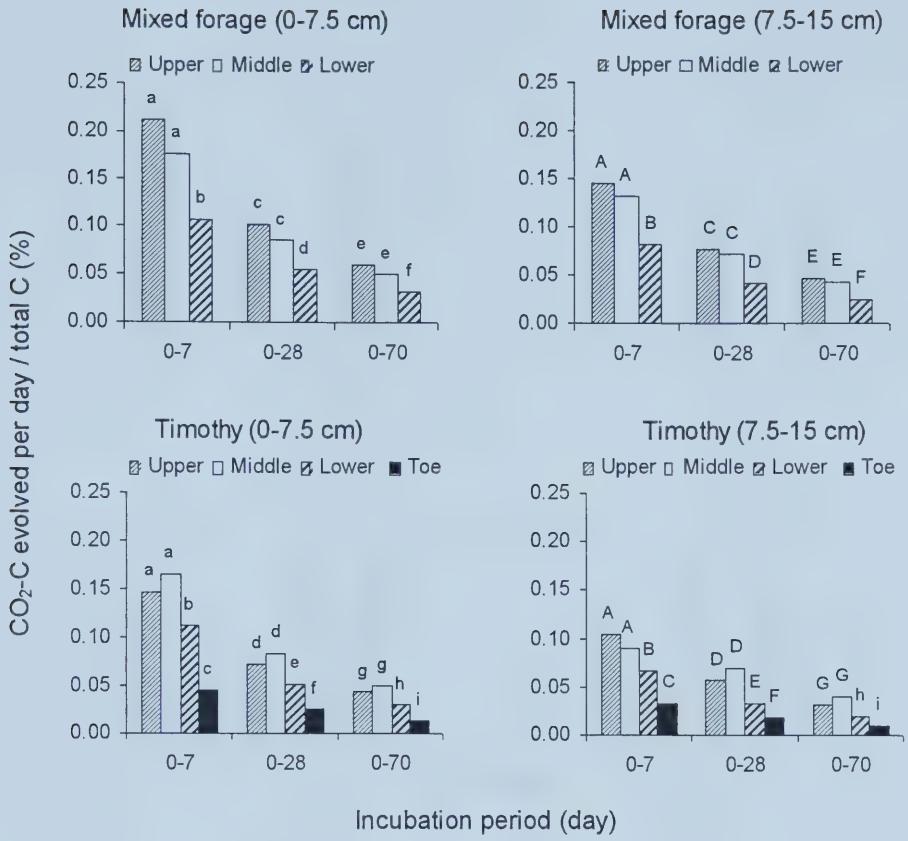

Fig. 2.3. Soil respiration expressed as a percentage of total C (cumulative CO_2-C/total C/time x 100) for specific time periods in soil samples taken from two fields in 10-wk incubation; LSD = 0.009. Bars carrying the same letter are not significantly different ($P < 0.05$).

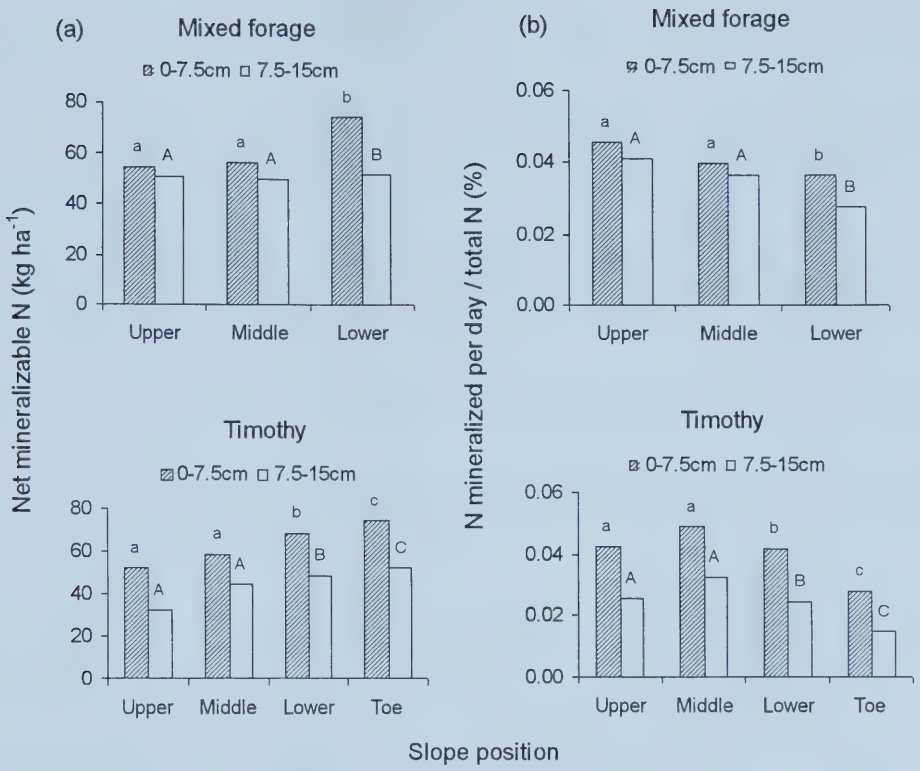

Fig. 2.4. (a) Net mineralizable N and (b) N mineralization rate expressed as a percentage of total N (net mineralizable N /total N x 100) for 70 days incubation in soil samples taken from two fields; LSD: Net mineralizable N = 13; Total N mineralized = 0.008. Bars carrying the same letter are not significantly different ($P < 0.05$).

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Chapter 3. Dynamics of Plant and Soil Microbial Biomass, and Soil Water and Temperature during Growing Season in Two Toposequences near Breton, Alberta

INTRODUCTION

Topography is known to play a key role in modifying both the microclimate and the hydrological conditions within a landscape. The influence of topography on the movement of water and the consequent redistribution of materials carried within the water can influence or control the type and intensity of soil processes within a landscape (Pennock et al., 1994). The low-lying areas of the landscape often have greater moisture content during the year. This increase in moisture is partially caused by surface run-off down the slope and by the water table, which gradually comes closer to the surface on the lower part of the slope. Spatial variation in soil water availability is related to soil depth and drainage patterns (Turner et al. 1997). It is the basic mechanism causing topographic differences in crop production, nutrient use efficiency, and the storage of soil C, N and P.

Changes in soil temperature and moisture greatly affect the physiological activity of soil microorganisms, rates of organic matter decomposition, and ecosystem C storage (Zak et al. 1999). At low soil temperatures, the rates of net mineralization are low, thereby reducing the availability of soil nutrients to plants. The temperature of soils is also related to soil moisture. A wet soil will warm up more slowly in spring than a dryer one because the specific heat of water (1.0 cal g^{-1}) is much higher than that of the soil (0.2 cal g^{-1}). Soil temperature is influenced by the water distribution in a toposequence if other factors such as aspect are fixed. Soils in the lower slope positions contain higher amount of water than soils in the lower slope positions. Therefore, it takes longer to reach freezing point in winter and to rise above zero degree in spring in the lower slope positions. However, little information has been provided on how soil temperature varies within toposequences.

Quantification of static and dynamic properties of soil in farm fields are needed for better resource management and environmental protection. Soil organic matter content, cation exchange capacity, and texture, do not change appreciably during a growing season. However, NO_3-N, soil moisture content, and grain yield exhibit seasonal and

annual variations (Wollenhaupt et al. 1997). Moisture deficits tend to limit plant production more in upland positions, where soils are more shallow and dry, than in lower slope positions. Slope positions greatly influenced the soil water and spring wheat yields in Brown Chernozemic soils in southwestern Saskatchewan, Canada (McConkey et al. 1996). In the non-drought years, wheat yields increased by 40% and crop water use efficiency increased by 20% from summit to toe slope positions. The wheat yields were positively correlated with 0-30 cm soil organic C concentration from different slope positions. Verity and Anderson (1990) found that lower crop yields at upper slope positions compared with those at lower slope positions was related to less water use and the greater top soil loss on upper versus lower slope positions.

Dynamics of fertilizer N in the barley-soil systems under conventional and zero tillage during the growing season were studied on the Eluviated Black Chernozem at Ellerslie research station (Haugen-Kozyra et al. 1993). Shoot and root ^{15}N recovery were high at ear emergence indicating a rapid uptake of mineral N pool. Mineral N (both NH_4-N and NO_3-N) was highest at the fifth leaf stage in both treatments and decreased by the ear emergence stage and remained low for the rest of the growing season. Microbial N was at the lowest during the ear emergence and at the highest during the grain filling stage in both treatments. Soil extractable N was greatest in the early growing season and least at mid season, but increased again at the end of the growing season in a tallgrass prairie soil N study conducted by Turner et al. (1997). A study assessed the topographic variability of the N contribution by ^{15}N labeled pea to the Chernozemic soils in Saskatchewan (Stevenson and van Kessel 1997). The ^{15}N from pea residue recovered in microbial biomass to a depth of 60 cm was higher in the foot slope position (71%) than in the shoulder position (51%), and related to the greater soil water content in the foot slope positions.

Variations in the soil microbial processes may enhance the efficiency of N use in agricultural systems. The size of soil microbial biomass or its turnover rates can affect crop growth. A large microbial biomass can maximize the nutrient use efficiency when crops are not growing, and then promote a steady release of nutrients during crop growth. Granatstein et al. (1987) observed a significant increase in microbial biomass after

harvest of winter wheat, and suggested that this might reduce N losses during the subsequent winter period. Total microbial biomass was the highest in early spring, and declined to about 67% of the initial values during the growing season in a Dark Brown Chernozem located at Saskatchewan (Bremer and van Kessel 1992). The decline of microbial biomass during summer might increase the nutrient supply for plant growth. Seasonal changes in microbial biomass in an arable and a grassland soil from the Rothamsted Classical Experiments seemed to be little (Patra et al. 1990). A gradual increase in microbial biomass occurred during a growing season on several Chernozemic soils in Western Canada and it was related to the rhizosphere and root exudates (Carter and Rennie 1984). Microbial biomass C and N remained relatively constant during a growing season in two northern hardwood ecosystems (Holmes and Zak 1994). Seasonal differences in soil microbial C and N could have been obscured by spatial variability (Ross and Tate 1993; Walley et al. 1996). Seasonal variations of soil microbial biomass along toposequences in Gray Luvisols of Breton was not measured.

Topography also exerts effects on soil nutrient concentrations. The relative availability of P, measured as $NaHCO_3$ extractable PO_4^{2-} to total P, increased down the slope by almost two-fold in short-grass steppe in Colorado, USA (Schimel et al. 1985). The NO_3-N supplying rate decreased over the growing season as the N uptake by wheat increased, which reflected the N assimilation by plants early in the growing season in the Brown soil zone of Saskatchewan (Jowkin and Schoenau 1998). The total amount of plant available inorganic N in the 0-60 cm among slope positions at the beginning of growing season decreased from foot to shoulder slope positions.

The objective of this experiment was to determine the effects of topography on soil moisture and temperature, and relate them to the spatial and temporal pattern of crop production, microbial biomass, soil moisture and nutrient dynamics along a toposequence.

MATERIALS AND METHODS

Sampling Methods

The experiment was conducted using a split plot design with the slope positions as main plot and soil depths as sub-plot on Mr. Flesher's farm which lies 110 km south-west of Edmonton (53° 05'N and 114° 27'W). A field with timothy grass and a field with mixed forages were chosen for the study. The landscapes were undulating to sloped upland. In the mixed forage field, five transects that cover upper, middle and lower slope positions were laid out in 1998. Because of the shape of the field, there were five replicates of sampling stations on the upper, four on the middle; and six on the lower positions, which gave a total of 15 sampling stations in the mixed forage field. In the timothy field, three transects that cover upper, middle, lower and toe slope positions were laid out at the same time. Three replicates of sampling stations per slope position were marked which gave a total of 12 sampling stations. The slopes ranged between 2-7%.

Three micro-loggers, Campbell Scientific CR 500 with digital recorder, were installed in the middle transect of the timothy field to cover the upper, middle and lower slope positions in July 1999. A second set was installed in the mixed forage field in November 1999. The temperature and TDR moisture probes (Campbell Scientific) were connected to the microloggers. They were inserted horizontally at the 30, 60, and 90 cm soil depths. The probe readings were recorded at one-hour intervals. The data were downloaded with a lap upper computer each month. The monitoring of soil moisture and temperature was conducted from July 1999 to May 2000.

Both fields were sampled every on June 7, 1999, June 28, 1999, and July 14, 1999. Soil and plant samples were taken within 1 m radius from each of the slope positions within the toposequences on June 7, 1999, June 28, 1999, and July 14, 1999. The above ground vegetation was harvested within a 0.25 m^2 frame, dried at 70 °C for 48 hr and plant dry mass was measured. A soil sampler was used to sample soil cores from 0-7.5 and 7.5-15 cm depths. Three soil cores were taken per depth and combined to form one sample. Soils were kept in a 2-5 °C cooler before analysis.

Analytical Methods

Plant total N, P and soil total P were measured by Kjeldahl digestion method. Soil total C and N were measured using Carlo Erba NA1500 nitrogen and carbon analyzer. Moist soil samples, 15 g of fresh soil without plant residues, were dried at 105 °C for 24 hr to obtain the gravimetric soil moisture contents. Soil microbial biomass C and N analyses were conducted on a 20 g oven dry soil basis by the chloroform fumigation incubation method by Jenkinson and Powlson (1976). A K_C factor of 0.41 was used in calculating biomass C. An average K_N factor of 0.22 was used for calculating biomass N. The K_N was determined by the equation: K_N = 0.014 x (CO_2-C from the fumigated sample without the control/ NH_4^+-N from the fumigated sample without the control) + 0.39 developed by Voroney and Paul (1984). Moist soil samples, on a 10 g oven dry basis, were extracted with 50 ml of 2M KCl for 1 hour, and the extracts were analyzed on Technicon Auto-analyzer for mineral N (NH_4^+-N and NO_3^--N). Moist soil samples, on a 5 g oven dry basis, were extracted with 25 ml of 0.03M NH_4F + 0.06M H_2SO_4 solution for 10 minutes, and the extracts were analyzed on Technicon Auto-analyzer for extractable PO_4-P.

The data were analyzed using a factorial split plot design consisting of four factors (date, field, slope position and or soil depth) using the General Linear Models Procedure of SAS (Statistical Analysis System, SAS Institute Inc. 1990). All results are means of all replicates in a specific position. Duncan's Multiple Range Test procedure was used for multiple comparison of main factors. The Shapiro-Wilk statistic of the Univariate and Multivariate Normality Tests was used to test for data normality.

RESULTS

Dynamics of Soil Temperature and Moisture Contents

The soil moisture content measured by TDR probes and the temperature measured by thermisters at 60 cm depth in the timothy field are shown in Fig. 3.1. The soil moisture content followed the order of lower> upper > middle; and the soil temperature followed by middle > upper > lower slope positions from July to November 1999. From the end of November, the soil temperature started to drop below 0 °C. However, the soils in the upper and middle slope positions reached 0 °C earlier than the lower slope position.

From December 1999 to March 2000, the lower slope position had higher soil temperature than that of the higher positions. By the end of March 2000, the soil temperature started to rise, but more rapidly in the upper and middle slope positions than the lower position. The lower slope position was still below 0 °C at that time. As the temperature of upper and middle slope positions rose above 0 °C, the water content increased, indicating thawing (April 18, 2000). The temperature of the lower slope position rose above 0 °C on April 30, 2000, later than the upper and middle slope positions.

Plant and soil dynamics in three sampling dates

PLANT DRY MATTER: There were significant differences of dry matter yields among different sampling dates. The dry matter yields increased as the growing season progressed. The plant dry matter yield showed no significant difference between two fields and among slope positions during the three sampling dates (Table 1). However, the trend of plant dry matter yield in the mixed forage field over the 3 sampling dates showed the following trend: upper > middle > lower. The trend of dry matter yield in the timothy field varied over the 3 sampling dates. On June 7 and June 29, 1999, the lower slope had highest yield followed by the toe slope position. On July 14, 1999, the toe slope had the highest yield followed by the middle slope position. Of all the three sampling time, the upper slope position of the timothy field had the lowest plant yield.

Total N yield of the plants was significantly different among slope positions and three dates (Table 3.1). In the mixed forage field, the N yield over all dates ranged from 92 – 129 kg ha^{-1}. The lower slope position of the mixed forage field had the lowest amount of N yield for all 3 sampling dates. The upper and middle slope positions had no significant difference in N yield. The June 29 sampling gave the highest total N yield for all the 3 slope positions in the mixed forage field. In the timothy field, N yield over all dates ranged from 52 – 168 kg ha^{-1}. The upper slope position had significantly lower amount of N yield, followed by the middle slope position. The lower and toe slope position had no significant difference in N yield. The N yield increased over time in the middle and toe slope position, and slightly increased in the lower slope position. The July 14 sampling gave the highest total N yield for upper slope position in the timothy field.

Plant total P yield was significantly different among sampling dates and slope positions (Table 3.1). In the mixed forage field, the total plant P yield over all dates ranged from 16.2 – 27.8 kg ha^{-1}. The P yield decreased from upper to lower slope positions for all three dates. There was no significant difference in total P yield between upper and middle slope positions, but the lower slope position had significantly lower total P yields. The P yield increased during the growing season. In the timothy field, the P yield over all dates ranged from 11.5 – 28.4 kg ha^{-1}. The upper slope position had significantly lower P yield, followed by the middle slope position. There was no significant difference in P yield between lower and toe slope positions for all 3 sampling dates. The P yield increased from June 7 to June 29, but the increase was not significantly different on July 14.

DYNAMICS OF SOIL MOISTURE AND POOLS: A summary of ANOVA of date, field, position, and depth effects of the soil properties obtained from three sampling dates during the growing season in 1999 is presented in Table 3.2. The soil volumetric moisture content was significantly different among sampling dates ($P < 0.01$) and slope positions ($P < 0.001$) (Table 3.2). For both fields, the soil moisture content on July 14, 1999 was significantly higher than the other two sampling dates, which were not significantly different. In the mixed forage field, there was no significant difference in soil moisture among slope positions (Fig. 3.2). Although statistically insignificant, the lower slope position had the highest amount of moisture content (30% v/v) while the middle slope position had the lowest (22% v/v). In the timothy field, there was no significant difference in moisture content among upper, middle and lower slope positions, but the toe slope position had significantly higher amount of moisture content (42% v/v). The middle slope position had the lowest amount of soil moisture (22% v/v). The measured moisture trends corresponded to those measured by the TDR probes in the timothy field, where the lower slope position had the highest water content and the middle had the lowest during the growing season (Fig. 3.1).

Soil microbial biomass C and N did not differ significantly over the sampling dates and between the fields. There was significant difference ($P < 0.001$) among slope positions in biomass C and N. As there was no statistical difference between the three

sampling dates for soil microbial biomass, the average data for the three dates were used to compare the difference among the slope positions (Fig. 3.3 a and b). The 7.5-15 cm soil depth had higher microbial biomass C and N than that of the 0-7.5 cm depth. Soil microbial biomass C and N followed the same trend, with the highest amount occurring in the toe slope position (481 kg ha^{-1} microbial C and 76 kg ha^{-1} microbial N in the 7.5-15 cm of the timothy field) followed by the lower slope position (421 kg ha^{-1} microbial C and 72 kg ha^{-1} microbial N in the 7.5-15 cm of the timothy field). The lowest amount of microbial C and N occurred in the upper and middle slope positions (261 kg ha^{-1} microbial C and 44 kg ha^{-1} microbial N in the 7.5-15 cm of the upper slope position of the timothy field). The upper and middle slope positions showed no significant difference in soil microbial C and N (Table 3.2; Fig. 3.3). The microbial C:N ratio for soils of all slope position was at around 6.

Soil respiration under laboratory condition showed no significant difference among different slope positions, at three sampling dates and between two soil depths (Table 3.2; Fig. 3.4). Although there was no difference statistically, the 0-7.5 cm soils had higher amount of C respired than the 7.5-15 cm soils. The toe slope position of the timothy field had relatively higher amount of C respired than the rest of the positions (Fig. 3.4). The date and position interaction indicates that the change of soil C respiration from different slope positions was different at different plant growing time.

Soil mineral N was significantly different between two fields and depths and among slope positions (Table 3.3). There were significant date, field, and slope position interactions implying that the change of mineral N was not consistent among different dates and slope positions, and between fields. The change of mineral N (NH_4-N and NO_3-N) was not the same in the 3 sampling dates. In general, the amount of mineral N in the timothy field (6.9 kg ha^{-1} by average) was higher than that in the mixed forage field (5.5 kg ha^{-1} by average); the 0-7.5 cm soil (7.3 kg ha^{-1}) had higher amount of mineral N than that of the 7.5-15 cm soil (5.0 kg ha^{-1}). On June 7, 1999, the highest amount of mineral N occurred in the lower slope position of both fields and depths. The upper and middle slope positions were not significantly different in mineral N contents. The lowest mineral N was in the 7.5-15 cm depth of the toe slope position (2.8 kg ha^{-1}). On June 29,

1999, the middle slope position had significantly higher amount of mineral N in both depths and fields (8.9-16.2 kg ha^{-1}). There was no significant difference between the upper, lower and toe slope positions. The lowest mineral N content was in the mixed forage field lower slope position and the timothy field upper slope position in the 7.5-15 cm depth (3.1 kg ha^{-1}). On July 14, 1999, there was no significant difference in mineral N content among all slope positions. Although statistically insignificant, the highest amount of mineral N was in the upper slope position 0-7.5 cm depth in the mixed forage field (20.3 kg ha^{-1}) and the lowest was in the toe slope position 7.5-15 cm in the timothy field (2.1 kg ha^{-1}).

Extractable PO_4-P was significantly different in dates, fields, slope positions and soil depths (Table 3.3). The timothy field had higher amount of PO_4-P (15.5 kg ha^{-1}) than that of the mixed forage field (9.5 kg ha^{-1}). The 0-7.5 cm soils had higher amount of PO_4-P (14.3 kg ha^{-1}) than that of the 7.5-15 cm soils (10.3 kg ha^{-1}). The PO_4-P content decreased from upper to toe slope positions. During the three sampling dates, the upper and middle slope positions had no significant difference in PO_4-P contents and they were higher than the lower and toe slopes. The lower and toe slope positions were not significantly different in the PO_4-P contents. Generally the PO_4-P decreased as growing season progressed.

ASSESSMENT OF MICROBIAL ACTIVITY: Carbon and N mineralized in the unfumigated soils samples during the 10-day incubation were used to calculated the relationship between mineralized C and N, microbial C and N, and soil total C and N. The average values of those ratios from soil samples collected on three sampling dates at different slope positions are shown in Table 3.4. There were significant differences in the ratios among different slope positions and two soil depths, but no difference among different sampling dates. The ratio of CO_2-C respired per day to soil total C and mineralized N per day to soil total N all decreased from upper to lower slope positions in both soil depths and both fields, which was consistent with the findings in Chapter 2. The 0-7.5 cm depth had higher ratios than the 7.5-15 cm. The ratio of respired C to soil total C decreased from upper to lower slope positions (1.1×10^{-3} - 3.8×10^{-4}) in the 0-7.5

cm depth (Table 3.4). The ratio of mineralized N rate to soil total N decreased from upper to lower slope positions (4.4×10^{-4} - 2.5×10^{-4}) in the 0-7.5 cm soil depth.

The ratios of microbial C to soil total C and microbial N to soil total N were not significantly different between two fields. The ratios were significantly different among slope positions and two soil depths. The 0-7.5 cm soils had lower ratios than the 7.5-15 cm soils. The microbial C to soil total C ratio decreased from upper to lower slope positions (1.08-0.71%) in the 0-7.5 cm soils. The microbial N to soil total N ratio followed the same trend (2.33-1.15% from upper to lower slope positions in the 0-7.5 cm soils). These trends were also consistent with the 10-wk incubation in Chapter 2.

The soil microbial metabolic quotient, which is the ratio of CO_2-C evolved to microbial C showed no significant difference between two fields, but significant differences among slope positions and two soil depths. The daily C metabolic quotient decreased in soils from upper to toe slope positions ($1.0 \times 10^{-1} - 5.8 \times 10^{-2}$ from upper to toe slope positions in the 0-7.5 cm soils). The 0-7.5 cm soils had higher C metabolic quotients than the 7.5-15 cm soils. The mineralized N rate to soil biomass N ratio showed no significant difference between two fields, but significant differences among slope positions and two soil depths. The ratio decreased from upper to toe slope positions (2.0×10^{-2} - 9.0×10^{-3} in the 0-7.5 cm soils). The ratios of the 0-7.5 cm soils were higher than that of the 7.5-15 cm soils.

DISCUSSION

The in situ measurement of soil moisture contents from upper, middle and lower slope positions corresponded to that of the field measurement during the sampling dates (Fig. 3.1 and 3.2). The lower slope position had much higher moisture content than the upper and middle slope positions as shown in both of the figures. Sutherland et al. (1993) found higher volumetric water content in soils from the depressional areas on an agricultural landscape with a mean slope of 2%. Jowkin and Schoenau (1998) also reported that the soil available moisture content in the 0-10 cm increased from footslope to shoulder positions over the growing season in southwestern Saskatchewan. However the difference was not statistically significant. The increased dry matter yield in the

lower slope positions of the timothy field correlated to the increase of soil moisture content. The same was not true for the mixed forage field. Excessive soil moisture in the lower slope positions may have limited plant growth, as it was over 100% of field capacity. The gleyed B horizon also indicated the water saturation in those soils.

Soil temperature was lower in the lower slope position than that in the upper and middle slope positions (Fig. 3.1). The upper and middle slope positions had very similar soil temperatures as the two curves overlap in Fig. 3.1. When spring started, the lower slope position warmed up more slowly than the other two slope positions because of higher soil water content. Cooler and wetter conditions reduce biological activities in soil which could account for much higher soil organic matter content in the lower slope positions over the long term as discussed in Chapter 2. Gleysolic soils were found in the lower slope positions indicating the low O_2 supply in soils of those slope positions. Therefore specific microbial activity could be slowed down in those soils. Soil temperature during the growing season was similar among different slope positions, which seemed not to have a distinctive effect on plant growth.

Soil microbial biomass C and N remained constant over the growing season from all slope positions (Fig. 3.3). Patra et al. (1990) also found that there was little seasonal fluctuations of microbial biomass in an arable and a grassland soil in the Rothamsted Classical Plots. They attributed the lack of variation to a relatively even litter input over time and the sampling error. More microbial C and N were found on the lower and toe slope positions. Greater soil water and C availability in the lower slope positions could lead to higher microbial biomass (Stevenson and van Kessel 1997). The 7.5-15 cm soils had slightly higher amount of microbial C than that of the 0-7.5 cm soil, the reason for this was unclear. The substrate availability did not seem to decrease from 0-7.5 cm to 7.5-15 cm soil depths. Soil C respiration in samples collected from three sampling dates during 10-day laboratory incubation showed no significant difference among different dates and slope positions. The values obtained in this 10-day incubation (Fig. 3.4) were similar to those values obtained during 0-7 days of the 10-wk incubation (Chapter 2, Fig. 2.2). Although the absolute amount of soil microbial biomass was higher in the lower

slope positions, the amount of C respired was not much higher in soils of those positions. The soil microbial biomass was less active in soils of the lower slope positions.

The ratios among soil mineralized C and N, microbial C and N, total C and N give better understanding of the biological activities of soils along the toposequences (Table 3.4). The ratio of soil C and N mineralized during the 10-day to total C and N decreased from upper to lower slope positions. The same trends were observed in the 10-wk incubation discussed in Chapter 2. The values for CO_2-C/total C on per day basis from this experiment were compared to those in the 10-wk incubation. For example, the upper position of the mixed forage field in the 0-7.5 cm soil had 0.11% of total C mineralized per day during the 10-day incubation, while it had 0.20% of total C mineralized per day during the 0-7 day in the 10-wk incubation. The mineralized N per day to soil total N ratios (Table 3.4) was consistent with those obtained in the 10-wk incubation (Chapter 2, Fig. 2.4 b). The longer the incubation, the smaller the rate of mineralization, as more resistant materials are left at the end of incubation. Soil samples used in the 10-wk incubation were air dried and then re-moistened. There could be an increase of mineralization due to drying and wetting. The samples used in this experiment were fresh soil samples collected right from field. This could lead to small differences in the results.

The ratios of biomass C/total C decreased from upper to lower slope positions. They were in the same range (0.7-1.7%) as those in the 10-wk incubation (Chapter 2, Fig. 2.1 b). Microbial N/total N also decreased from upper to lower slope positions correspondingly (2.33-1.15% from upper to toe). Microbial biomass C accounts for 1-3% of the soil total C, whereas microbial biomass N accounts for 2-6% of the soil total N (Jenkinson 1987; Brookes et al. 1985). Our results for biomass C and N were well within this range. Soil metabolic quotients (for both C and N) both decreased from upper to lower slope positions (Table 3.4). These results indicated that the soil organic matter quality was different in soils from different slope positions (also refer to Chapter 2). The soils of lower slope positions had a larger proportion of more resistant organic matter pool. Proportionally larger amount of non-microbial C and N was contained in the total soil organic matter fraction in those soils. Sparling (1992) pointed out that the stabilized

C in the organic C fraction could greatly influence the microbial C to total organic C ratio of a soil. Results obtained in this experiment further strengthen the points discussed in Chapter 2.

The spatial difference in plant yield might have been more distinguished under a drier growing season year, however the season under study was quite wet. In the mixed forage field, the plant dry matter, N and P yield decreased from upper to lower slope positions (Table 3.1) for all three sampling dates. The lower slope position of the mixed forage field had Gleyed Dark Gray Chernozem and some Orthic Humic Gleysols. The poorer drainage in these soils might have resulted in slower rate of plant production. The water table was high, which might lead to waterlogging and hence lower plant production. The soil moisture content in the 0-15 cm depth of the lower slope position was 32% v/v, which was much higher than its field capacity soil water content (26%, v/v). Anaerobic condition could occur and affect nutrient uptake by plants in soils of lower slope positions. Plant available mineral N and PO_4-P tended to be lower in the lower slope position and plant available decreased from upper to lower slope positions (Table 3.2). These all correlated to the plant dry matter, N and P yields, which decreased from upper to lower slope positions.

In the timothy field, however, the upper slope position had the lowest yields and the lower slope position had the highest yields. On July 14, the end of the growing season, the toe slope position had the highest yields. The toe slope positions of the timothy field had 42% v/v moisture content by average in the 0-15 cm soil depth, while in the upper slope positions there was 22% v/v moisture. The higher soil surface moisture supported better growth. Plant total N and P decreased over the growing season as plants matured. This decrease could be due to the initial accumulation of N and P in the early growth followed by later dry matter accumulation, which dilute the N and P content. Our data was consistent with those found by Jowkin and Schoenau (1998). The toe slope positions had much lower mineral N and extractable PO_4-P contents especially in the 7.5-15 cm depth (Table 3.3). These trends corresponded to the increase of plant N and P yields from upper to toe slope positions (Table 3.1). Excessive plant biological uptake caused the depletion of the soil nutrient pools. The increase of plant yield also corresponded to

the increase of absolute N mineralization rates and the MOM fraction from upper to toe slope position (Refer to Chapter 2). Mineral N and extractable PO_4-P varied greatly in the fields, due to the effect of fertilization and the labile nature of these nutrient pools.

Better understanding of the C and N fluxes at different landscape positions is needed. The potential mineralizable C and N pools and their relationship with soil total organic matter need to be evaluated at different slope positions in a typical Breton landscape.

Table 3.1. Plant dry matter, total N and P collected at three sampling dates

Slope Position	June 7/1999	June 29/1999	July 14/1999
		Plant Dry Matter (kg ha^{-1})	
		Mixed forage field	
Upper	4950 a	6310 a	7320 a
Middle	4680 a	5270 a	7140 a
Lower	3890 b	4800 b	5590 a
		Timothy field	
Upper	2520 a	5250 a	5490 a
Middle	3320 a	5400 a	6960 a
Lower	3770 b	6830 a	6780 a
Toe	3460 c	6470 a	8340 a
		N yield (kg ha^{-1})	
		Mixed forage field	
Upper	117 Aa	129 Ba	112 Ca
Middle	107 Aa	123 Ba	118 Ca
Lower	92 Ab	97 Bb	96 Cb
		Timothy field	
Upper	52 Ab	79 Bb	56 Cb
Middle	91 Ab	105 Bb	128 Ca
Lower	133 Aa	133 Bc	138 Ca
Toe	123 Aa	136 Bc	168 Ca
		P yield (kg ha^{-1})	
		Mixed forage field	
Upper	23.2 Aa	26.2 Ba	27.8 Ba
Middle	20.4 Aa	22.3 Ba	25.8 Bb
Lower	16.2 Ab	16.9 Bb	17.8 Ba
		Timothy field	
Upper	11.5 Ac	16.9 Bc	16.2 Bc
Middle	16.8 Ac	18.0 Bc	21.3 Bc
Lower	17.3 Ad	26.6 Bd	23.5 Bd
Toe	16.0 Ad	28.4 Bd	25.9 Bd

Summary of ANOVA

Source of variation	d.f.	Plant dry matter	N yield	P yield
Date	2	***	***	***
Field	1	NS	NS	NS
Position	3	NS	***	***
Field × Position	3	***	***	***
Field × Date	2	NS	***	NS
Position × Date	6	NS	NS	NS
Field × Position × Date	6	NS	NS	NS

For each row and column, values of each variable marked with the same letter are not significantly different (P<0.05); Uppercase letters are comparisons among sampling dates for a specific slope position, lowercase letters are comparisons among slope positions, depths and fields for a specific sampling date.

*, **, *** $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively; NS, not significant.

Table 3.2. Summary of ANOVA for biomass C, biomass N, soil C respiration and volumetric moisture content of soil samples from two depth collected on three sampling dates in summer of 1999

Source of variation	Summary of ANOVA			
	Moisture content	Biomass C	Biomass N	Soil C respiration
Date	**	NS	NS	NS
Field	NS	NS	NS	NS
Position	***	***	***	NS
Depth	NS	*	NS	NS
Date x Field	NS	NS	***	NS
Date x Position	NS	NS	NS	*
Field x Position	NS	NS	***	NS
Date x Field x Position	NS	NS	NS	NS

*, **, *** $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively; NS, not significant.

Table 3.3. Soil mineral N (NH_4-N and NO_3-N) and extractable PO_4-P on three sampling dates.

Slope Position	June 7/1999	June 29/1999	July 14/1999
	Mineral N (kg ha^{-1} soil)		
	Mixed forage field		
	0-7.5 cm		
Upper	3.2 Aa	6.9 Ba	20.3 Ca
Middle	3.4 Aa	10.2 Bb	9.9 Cb
Lower	4.5 Aa	4.02Ba	4.9 Cb
	7.5-15 cm		
Upper	2.8 Ab	3.2 Ba	3.8 Cc
Middle	2.7 Ab	8.9 Bb	10.4 Cc
Lower	3.0 Ab	3.1 Ba	2.3 Cc
	Timothy field		
	0-7.5 cm		
Upper	3.2 Ac	4.4 Bc	5.9 Ca
Middle	5.4 Ac	16.2 Bd	6.1 Ca
Lower	16.1 Ad	6.1 Be	10.0 Ca
Toe	13.5 Ae	7.8 Be	5.0 Ca
	7.5-15 cm		
Upper	3.1 Ad	3.1 Bc	12.8 Cb
Middle	4.1 Ad	15.6 Bd	15.8 Cb
Lower	9.4 Ad	5.4 Be	4.2 Ca
Toe	2.8 Ae	5.2 Be	2.1 Ca
	Extractable PO_4-P (kg ha^{-1} soil)		
	Mixed forage field		
	0-7.5 cm		
Upper	21.1 Aa	16.4 Ba	8.9 Ca
Middle	16.0 Aa	15.2 Ba	5.5 Ca
Lower	5.4 Ab	5.5 Bb	1.4 Cb
	7.5-15 cm		
Upper	15.7 Ac	16.5 Ba	11.9 Ca
Middle	14.2 Ac	11.8 Ba	4.4 Ca
Lower	3.18 Ad	5.0 Bb	1.4 Cb
	Timothy field		
	0-7.5 cm		
Upper	22.3 Aa	25.1 Ba	20.9 Ca
Middle	31.1 Aa	29.0 Ba	23.9 Ca
Lower	13.4 Ab	16.1 Bb	28.8 Ca
Toe	10.0 Ab	5.3 Bb	7.4 Cb
	7.5-15 cm		
Upper	18.9 Ac	19.9 Ba	32.0 Ca
Middle	21.7 Ac	18.9 Ba	10.9 Ca
Lower	8.4 Ad	10.7 Bb	8.4 Cb
Toe	5.6 Ad	4.3 Bb	2.4 Cb

Table 3.3. (Continued)

Summary of ANOVA		
Source of variation	Mineral N	Extractable PO4-P
Date	NS	*
Field	***	***
Position	*	***
Depth	**	**
Date x Field	NS	NS
Date x Position	***	NS
Field x Position	***	NS
Date x Field x Position	***	NS

For each row and column, values of each variable marked with the same letter are not significantly different (P<0.05); Uppercase letters are comparisons among sampling dates for a specific slope position, lowercase letters are comparisons among slope positions, depths and fields for a specific sampling date.

*, **, *** $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively; NS, not significant.

Table 3.4. Ratios of mineralized C and N over a period of 10-day laboratory incubation, microbial C and N to soil total C and N, CO_2-C evolved during 10-day to microbial C (metabolic quotient) and ratio of mineralized N to biomass N from soils collected on three sampling dates.

Slope Position	CO_2-C day^{-1}/ total C	Microbial C / total C (%)	CO_2-C day^{-1}/ microbial C
	Mixed forage field		
	0-7.5 cm		
Upper	1.1×10^{-3} a	1.08 a	1.0×10^{-1} a
Middle	9.5×10^{-4} a	1.07 a	6.0×10^{-2} b
Lower	6.7×10^{-4} b	0.94 b	5.9×10^{-2} b
	7.5-15 cm		
Upper	5.4×10^{-4} c	1.68 c	3.3×10^{-2} c
Middle	5.8×10^{-4} c	1.56 c	4.4×10^{-2} c
Lower	4.1×10^{-4} d	1.41 d	2.9×10^{-2} d
	Timothy field		
	0-7.5 cm		
Upper	5.9×10^{-4} a	0.94 a	6.3×10^{-2} a
Middle	6.2×10^{-4} a	0.95 a	6.5×10^{-2} a
Lower	3.8×10^{-4} b	0.80 b	4.8×10^{-2} b
Toe	4.1×10^{-4} b	0.71 b	5.8×10^{-2} b
	7.5-15 cm		
Upper	4.4×10^{-4} c	1.28 c	3.4×10^{-2} c
Middle	4.2×10^{-4} c	1.18 c	3.5×10^{-2} c
Lower	2.5×10^{-4} d	1.14 d	2.2×10^{-2} d
Toe	2.8×10^{-4} d	1.00 d	2.8×10^{-2} d
	Mineralizable N day^{-1}/total N	Microbial N/total N (%)	Mineralizable N day^{-1}/microbial N
	Mixed forage field		
	0-7.5 cm		
Upper	4.0×10^{-4} a	2.10 a	2.1×10^{-2} a
Middle	3.8×10^{-4} a	2.23 a	1.3×10^{-2} a
Lower	2.7×10^{-4} b	1.93 b	9.0×10^{-3} b
	7.5-15 cm		
Upper	3.7×10^{-4} c	2.39 c	1.6×10^{-2} c
Middle	2.3×10^{-4} d	2.35 c	1.4×10^{-2} c
Lower	1.9×10^{-4} d	2.12 d	9.0×10^{-3} d
	Timothy field		
	0-7.5 cm		
Upper	4.4×10^{-4} a	1.85 a	2.4×10^{-2} a
Middle	4.9×10^{-4} a	1.91 a	2.7×10^{-2} a
Lower	3.8×10^{-4} b	1.61 b	2.1×10^{-2} b
Toe	2.5×10^{-4} b	1.67 b	1.5×10^{-2} b
	7.5-15 cm		
Upper	2.7×10^{-4} c	2.47 c	1.4×10^{-2} c
Middle	2.6×10^{-4} c	2.59 c	1.2×10^{-2} c
Lower	2.3×10^{-4} d	2.15 d	9.0×10^{-3} d
Toe	1.9×10^{-4} d	1.89 d	9.0×10^{-3} d

For each row and column, values of each variable marked with the same letter are not significantly different.

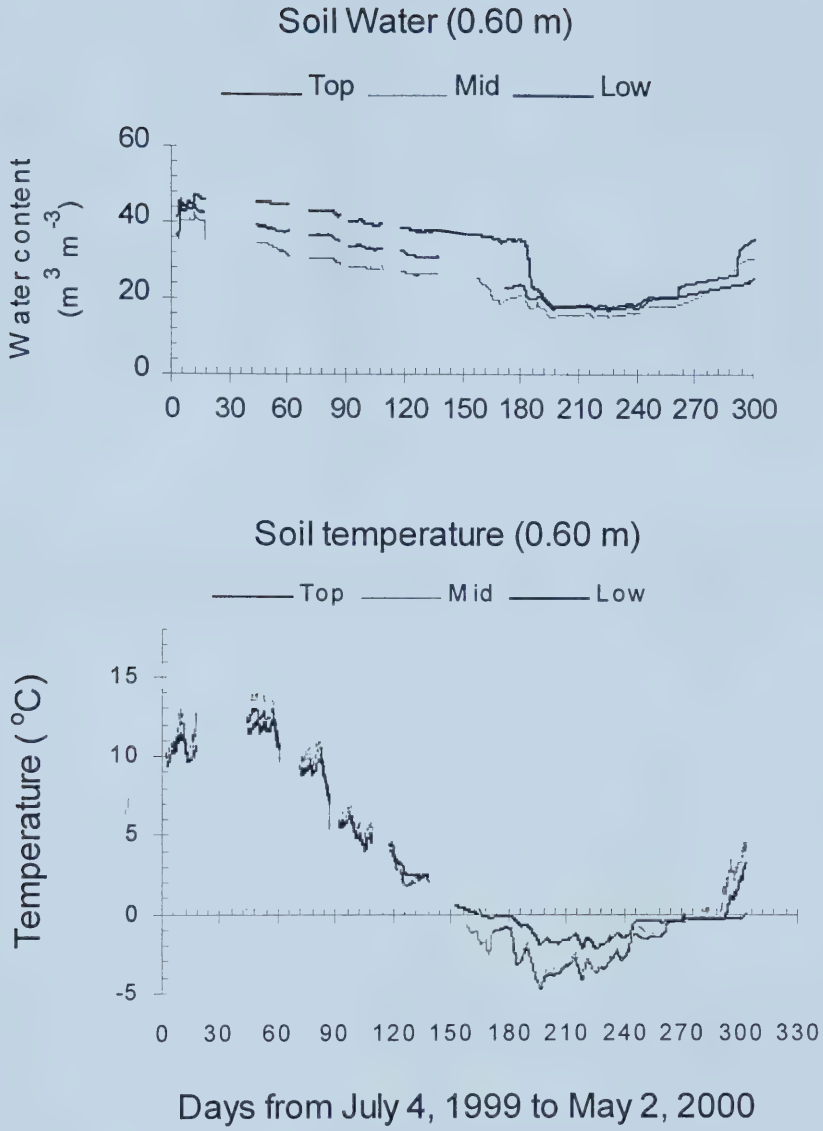

Fig. 3.1. TDR probe measured soil volumetric water content and soil temperature at three slope positions at 60 cm depth in the timothy field.

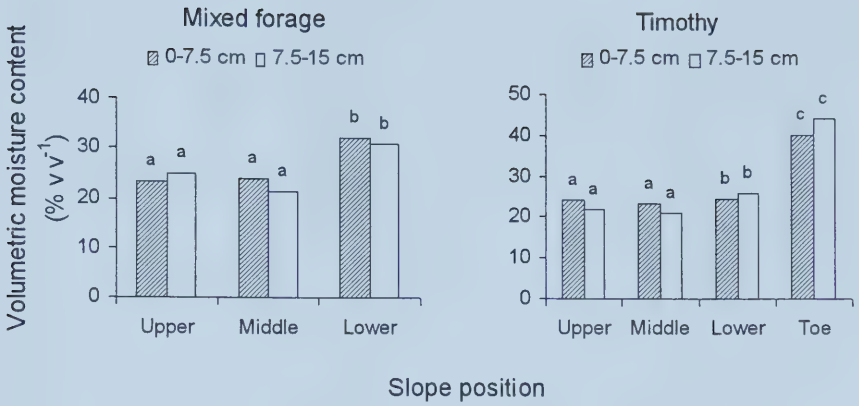

Fig. 3.2. Soil volumetric moisture contents at different slope positions from two fields in 1999, average of the three sampling dates; LSD = 3.7. Bars carrying the same letter are not significantly different ($P < 0.05$). Bars carrying the same letter are not significantly different ($P < 0.05$).

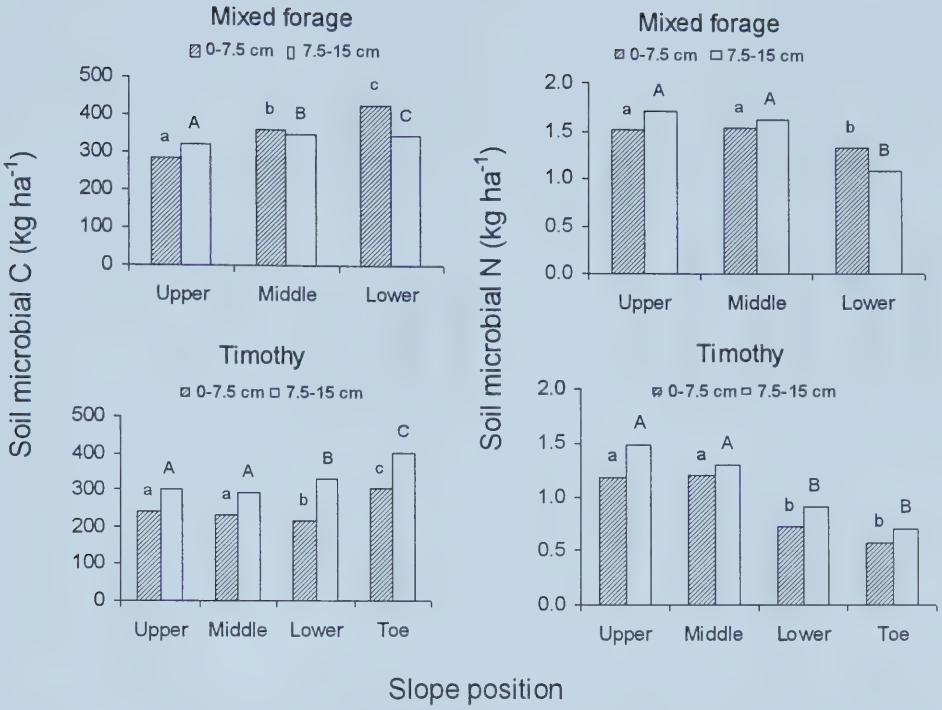

Fig. 3.3. Soil microbial biomass C and N at different slope positions from two fields in 1999, average of the three sampling dates. LSD: Biomass C = 95, Biomass N = 12. Bars carrying the same letter are not significantly different ($P < 0.05$). Bars carrying the same letter are not significantly different ($P < 0.05$).

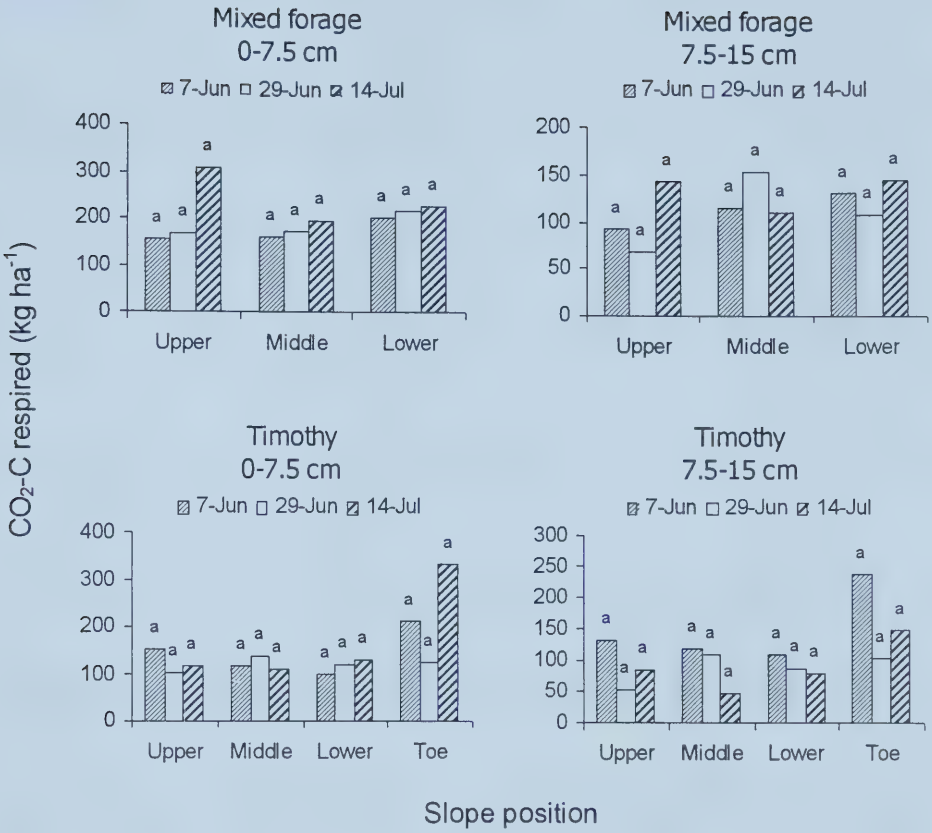

Fig. 3.4. Microbial respiration of soil samples from different slope positions, two depths and two fields collected on three sampling dates (10-day laboratory incubation at 22 °C and 80% of field capacity moisture contents).

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Chapter 4. Dynamics of Carbon, Nitrogen and Phosphorus under Laboratory Conditions in Soil Samples from Two Toposequences

INTRODUCTION

Slope, aspect, and landscape position determine the amount of water stored in a particular soil (Hanna et al. 1982). The hydrological processes within toposequences control various soil types and soil activities. For example, denitrification rates were highest in footslope positions and lowest in shoulder positions in the Brown soil zone of southern Saskatchewan (Pennock et al. 1992; Van Kessel et al. 1993). Soil respiration was highest in the depression areas of an agricultural landscape (Sutherland et al. 1993). Highest laboratory and in-situ N mineralization rates were found in the footslope position in a soil catena of shortgrass steppe (Schimel et al. 1985). These soil processes in turn influence plant growth. The rate of N_2 fixation in a semi-arid environment was highest on the footslopes due to the greater water availability (Mahler et al. 1979). Measuring soil activities at different slope positions give insights to C sequestration and greenhouse emission in a landscape level.

The ^{15}N isotope labeling technique has been used to study the fate of fertilizer applied to soils, N cycling in the soil-plant system, and in the kinetic analysis of the decomposition of the soil organic matter fractions under laboratory, greenhouse or field conditions. Numerous experiments have been conducted around the world to assess the efficiency of different forms of fertilizer, time of application, method of application and placement of fertilizer (Olson and Kurtz 1982). Due to biological processes and continuous interchange of N between the organic and inorganic forms in soil, the ^{15}N label gets incorporated in plants and in different fractions of soil organic matter. The ^{15}N labeled soil has been used under laboratory, greenhouse and field conditions to discern the dynamics of different forms of organic matter (Jansson and Persson, 1982).

Evaluation of soil N status may involve measurement of a number of soil pools such as soil mineral N and microbial biomass. The soil active N pools accounted for 5-15% of soil N as determined by the isotope dilution techniques (Paul and Juma 1981). Soil microbial biomass can be used as an indicator of the ability of the soil to store and

recycle N (Gregorich et al. 1994). The extent of soil organic matter turnover is controlled by the size and activity of soil microbial biomass and the existing environmental conditions (Martens 1995). Microbial size and activity can be expressed as an absolute basis (per gram of soil) or on a relative basis (per gram of soil carbon). Although the total soil organic C and N was almost three fold greater in the Black Chernozemic soil at Ellerslie compared to the Gray Luvisol at Breton, the relative rates of CO_2-C respired (CO_2-C/g soil C) and net N mineralized (NO_3^--N/g soil N) were lower in the Black Chernozem (Rutherford and Juma 1989). Therefore, the expression of data in absolute and relative term can yield greater insights into microbial activities in different soils.

Soils along a toposequence usually exhibit different morphologies. Distribution of soil properties varies as a function of landscape morphology and moisture regime (Donald et al. 1993). Novak and Bertsch (1991) studied the humic substances in soil organic matter from a transect in Colorado. They showed that topography might have modified the formation of humic substances in soil organic matter from different slope positions. Greater C turnover from upland soils reduced the residence time of humic acid precursors and those compounds were redistributed to the bottomland soils, therefore formed higher amount of humic substances._Microbial response to topographic effect on moisture and nutrient redistribution within a landscape can influence the potential for nutrient losses (Turner et al. 1997). High water content might reduce N availability by anaerobic conditions leads to_denitrification, by nitrification and subsequent leaching loss, or by increasing uptake of available N.

The kinetics of net soil N mineralization has been studied using the leaching-incubation technique of Stanford and Smith (1972). The data have been analyzed using zero-order (Tabatabai and Al-Khafaji 1980), first order (Bonde and Lindberg 1988; Chae and Tabatabai 1986), and the double exponential (Molina et al. 1980) models. These kinds of studies have been done for a wide variety of soils. Ajwa et al. (1998) compared net C and N mineralization for both tall grass prairie and agricultural soil profiles by a 40-wk incubation experiment. The ratio of potentially mineralizable N to total N was greater in the agricultural soil profile than in the soil profile under the tall grass prairie. At the Breton plots, the 8-yr cereal-forage agroecological rotation with green manure had

higher potentially mineralizable N than the 5-yr cereal-forage classical Breton rotation with no return of crop residues (Wani et al. 1993).

There is very limited information on the spatial distribution of soil C and N mineralization in toposequences adjacent to the Breton plots. The purpose of this study is to compare the soil microbial activities in soils from different slope positions by incubating ^{15}N labeled soils, collected from the field, under laboratory conditions. The objectives of the study were to: (i) assess the dynamics of C, N and P and soil microbial biomass activity in soil samples from different slope positions of the two fields; and (ii) determine the C and N mineralization rates and N potentials in soils collected from different slope positions at a Breton farm field under standardized laboratory conditions.

MATERIALS AND METHODS

Experimental design and labeling method

Three transects that covered all the slope positions of the forage and timothy fields were chosen to obtain ^{15}N labeled soil samples for laboratory incubation experiment. Metal frames (45 cm x 45 cm x 15 cm) were installed into the soil in May 1999. Nine metal frames were installed in the mixed forage field (3 slope positions × 3 replicates) and 12 in the timothy field (4 slope positions × 3 replicates). In order to evenly label the soil, all the above ground vegetation within the metal frames were cut to the soil surface. A plastic mesh (9 cm x 9 cm cell size) was placed inside the metal frame and 40 mL of ^{15}N labeled urea (99.9% atom abundance applied at the rate of 2 kg N ha^{-1} soil) was injected into the soil with a syringe in the middle of each square. One L of de-ionized water was evenly applied on to the labeled soil to allow further penetration of the labeled urea. There was not much re-growth within the frame during the growing season. The above ground vegetation in the frame was harvested before the whole field was cut.

Field sampling of ^{15}N labeled vegetation and soils was conducted in October 1999. All the above ground vegetation within the frame was cut to the soil surface. The soil within the frame was excavated to a depth of 12.5 cm, weighed on a scale and mixed on a plastic sheet. One kg soil sample was taken from each frame. The rest of the ^{15}N labeled

soil was returned to the frame. All the plant samples were oven dried at 70°C for 48 h and all soil samples were kept at 5°C in a cold room before analysis.

Laboratory Incubation and Analytical Methods

THE 16-WK INCUBATION EXPERIMENT: In order to evaluate the soil C and N mineralization, and microbial biomass C, N, P dynamics under standard conditions, an incubation experiment with soil samples (mixed forage field: 3 slope positions x 3 replicates = 9; timothy field: 4 slope positions x 3 replicates = 12; total of 21 samples) was conducted. The bulk soil samples were divided into 7 sets which were destructively sampled on wk 0, 2, 4, 6, 8, 12, and 16. For each set, field moist soils (70 g oven-dry equivalent) were weighed into polyethylene specimen cups and adjusted to 80% field capacity moisture contents. Each of the soil samples was placed in a 2 L Mason jar. A 25 mL 0.25 M NaOH trap was placed in the jar to trap the CO_2 evolved from the soil and a vial containing 10 mL of water was also placed in the jar to maintain the humidity. All jars were sealed and incubated at 22°C in the dark. Soil samples were aerated and moistened to 80% of field capacity, if necessary, every four weeks during the incubation period.

On each sampling day, the CO_2 traps were titrated with 0.25 M standardized HCl solution. For each sample, 20 g moist soil was extracted with 80 mL 2 M KCl for 1 h for mineral N analysis. The NO_3^--N in these samples was analyzed for ^{15}N abundance. Another two 20 g portions were used for microbial biomass C and N measurements. One portion was fumigated with ethanol free chloroform for 24 h while the other left unfumigated. Both the fumigated and unfumigated soils were incubated at 22°C for 10 days. The soils were then extracted with 80 mL 2 M KCl for 1 h and the filtrates analyzed for mineral N contents. The NH_4^+-N in the fumigated and incubated soil samples was analyzed for ^{15}N abundance and represented the ^{15}N abundance of biomass N. The soil extracts were prepared by diffusion method as described by Brooks et al. (1989). The ^{15}N trapped on the diffusion disks was analyzed on a mass spectrometer, model SIRA 10 (Stable Isotope Ratio Analyzer).

Soil microbial biomass C was calculated based on the amount of CO_2 evolved during the 10-day incubation by chloroform fumigation-incubation method (Jenkinson and Powlson 1976) using a K_C factor of 0.41; biomass N was based on the difference between fumigated and unfumigated extractable mineral N using an average K_N factor of 0.22. The K_N was calculated from the equation: $K_N = -0.014 (Cf/Nf) + 0.39$ where Cf is the amount of CO_2-C evolved from the fumigated sample and Nf is the amount of NH_4^+-N from the fumigated sample (Voroney and Paul 1984). A moist soil sample (5 g) was extracted with 25 mL of 0.03 M NH_4-F + 0.06 M H_2SO_4 solution for 10 min and the resulting filtrates were analyzed for extractable PO_4-P on the Technicon Autoanalyzer.

Soil microbial biomass P was only conducted on wk 0 and wk 16 using the method of Brookes et al. (1981). Briefly, 3 portions of 5 g oven-dry equivalent moist soil were used. The first portion was fumigated with chloroform for 24 h at 22°C, and the other two were incubated aerobically at the same period. The fumigated and one of the unfumigated soil samples were then extracted with 100 ml 0.5 M $NaHCO_3$. The third portion was extracted with 100 mL 0.5 M $NaHCO_3$ plus 25 μg P g^{-1} KH_2PO_4. The $NaHCO_3$ plus KH_2PO_4 was used for to correct the P adsorbed by soil particles. The phosphate in the extract was measured by reacting it with ammonium molybdate to form a molybdate color complex, which was measured at 712 nm wavelength using a spectrophotometer.

THE 16-WK INCUBATION-LEACHING EXPERIMENT: Soil samples from each of the slope positions of the two fields were used (mixed forage field: 3 slope positions x 3 replicates = 9; timothy field: 4 slope positions x 3 replicates = 12; total of 21 samples). The initial gravimetric moisture contents were obtained on those soil samples. Moist soil (50 g oven-dry equivalent) was mixed with 50 g washed Ottawa sand and put into a PVC leaching tube (15 cm long, 5.5 cm i.d.), which was lined with a glass fiber filter paper (Fisherbrand circles G6#09-804-90A) at the bottom of each tube. A small amount of fiber glass wool was put on upper of the soil and sand mixture to avoid soil dispersion during leaching. The PVC tubes were incubated aerobically at 22°C in the dark for a total of 16 wk. The soil samples were initially leached with 75 mL 0.01 M $CaCl_2$ followed by 25 mL N-minus nutrient solution. All the solutions were added in small increments, the

soil tubes were put under vacuum at about 33 kPa moisture tension after free drainage ceased. All the leachates were collected and filtered when necessary. Mineral N (NH_4-N and NO_3-N) was analyzed on Technicon Auto-analyzer. The soil samples were leached on week 2, 4, 6, 8, 12, and 16. This experiment was simultaneously conducted with the incubation experiment described earlier.

The soils used for this 16-wk experiment were ^{15}N labeled field fresh soil. They differ from soils samples used in the 10-wk incubation experiment (Chapter 2), in which the macro-organic matter was removed and samples were all air-dried and sieved. The method of soil microbial biomass measurement used in 10-wk incubation was fumigation-extraction method, where in this experiment was fumigation-incubation method. The dynamics of soil biomass C, N and P were measured with more accuracy and frequency in the 16-wk experiment.

Statistical Analysis

The Shapiro-Wilk statistic of the Univariate and Multivariate Normality Tests was used to test for data normality and all were normally distributed. A mixed model analysis of variance using a nested design in which slope position was nested within the field was used to compare the C and N mineralization with repeated measurement statement in SAS (SAS Institute Inc., 1990). All results are means of all replicates in a specific position. The LSMEANS was used to test the differences in means.

RESULTS

Total C and N content

The soil total C and N concentrations in 0-12.5 cm depth were not significantly different between two fields but there was a significant difference among slope positions (Table 4.1). In the mixed forage field, there was no significant difference in total C content between upper and middle slope positions (22,700 and 27,000 mg kg^{-1} soil, respectively). The lower slope had significantly higher amount of total C (33,600 mg kg^{-1} soil). In the timothy field, there was no difference in total C between upper and middle slopes (27,600 and 26,700 mg kg^{-1} soil, respectively). The lower and toe slope position had significantly higher amount of total C (55,600 and 132,300 mg kg^{-1} soil,

respectively). Total N content showed a consistent trend with the total C content along different slope positions. The total N of the toe slope position (9,270 mg kg^{-1} soil) was almost four times greater than that of the upper slope position (2,390 mg kg^{-1} soil) in the timothy field.

The amount of total C and N in soil samples from 0-12.5 cm depth from different slope positions showed similar trends to those of the samples obtained from the field experiment (Table 2.3). Higher C/N ratio was measured in the lower slope positions as found in the previous measurement (Chapter 2).

Microbial biomass C, N, and P dynamics

There were no significant changes in the amount of microbial biomass C (Fig. 4.1) over the 16-wk period ($P < 0.05$) for all soils from different slope positions. However, there was a significant difference in the amount of microbial C between the two fields, and among different slope positions. In general, the timothy field had higher amount of microbial C than that of the mixed forage field. In the mixed forage field, the microbial C was not significantly different between upper and middle slope positions during incubation. The average microbial C in the upper slope position was 360 mg kg^{-1} soil compared to 460 mg kg^{-1} soil for the middle slope position. The microbial C in lower slope position (650 mg kg^{-1} soil) was significantly higher than that of the upper and middle slopes. There was no significant difference in microbial C between upper and middle slope positions in the timothy field (Fig. 4.1). The average amount of microbial C in the toe slope position (1,500 mg kg^{-1} soil) was significantly greater than that in the lower slope positions (822 mg kg^{-1} soil).

Soil biomass N showed significant difference over time, between two fields and among slope positions. Generally, soil microbial N decreased over the 16-wk incubation (Fig. 4.2). The microbial N gradients for soils of the mixed forage field were -0.55, -1.45 and -1.42 mg kg^{-1} soil day^{-1} for upper, middle and lower slope positions, respectively. The gradient of biomass N in the upper slope position was significantly lower than that of the middle and lower slope positions. There was no significant difference the microbial N gradients of middle and lower slope positions. The microbial N gradients of the

timothy field were -1.88, -0.91, -1.69 and -2.73 mg kg^{-1} soil day^{-1} for upper, middle, lower and toe slope positions, respectively. There was no significant difference in the microbial N gradients for upper, middle and lower slope positions. The toe slope position had a significantly higher microbial N gradient.

Soil microbial biomass ^{15}N in soils of different slope position during 16-wk is shown in Fig. 4.3. The microbial ^{15}N decreased in all soils from the beginning to the end of the experiment. The microbial ^{15}N gradients for soils of the mixed forage field were -1.08, -1.76 and -1.70 mg kg^{-1} soil day^{-1} for upper, middle and lower slope positions, respectively. The microbial ^{15}N gradient of the upper slope position was significantly lower than that of the middle and lower slope positions. The microbial ^{15}N gradients of middle and lower slope positions were not significantly different. The microbial ^{15}N gradients of soils from the timothy field were -2.48, -1.30, -3.12 and –3.02 mg kg^{-1} soil day^{-1} for upper, middle, lower and toe slope positions, respectively. There was no significant difference in the microbial ^{15}N gradients between upper and middle slope positions. The toe and lower slope position had significantly higher gradients from which they were not significantly different from each other.

Microbial biomass P measured in soils incubated at the beginning and the end of the 16-wk experiment showed a significant difference in slope positions (Table 4.2). In the mixed forage field, there was no significant difference in microbial P among different slope positions, and between the two incubation dates. However the microbial P in the lower slope position was higher than the upper and middle slope positions in both days (36 mg kg^{-1} soil at the initial and 48 mg kg^{-1} soil at the end of the incubation). In the timothy field, the microbial P was not significantly different among upper, middle and lower slope positions at the initial incubation (Table 4.2). However the microbial P in the toe slope position was significantly higher (76 mg kg^{-1} soil). The microbial P was not significantly different between upper and middle slope position at the end of incubation (34 and 35 mg kg^{-1} soil, respectively). But the microbial P in the lower and toe slope positions was significantly higher (87 and 88 mg kg^{-1} soil, respectively).

Carbon and nitrogen mineralization

There was no significant difference in cumulative CO_2-C evolved between the two fields during the 16-wk incubation (Table 4.3 and Fig. 4.4). In the mixed forage field, the upper slope position was significantly lower (1,130 mg kg^{-1} soil) than that of middle and lower slope positions in the amount of CO_2-C mineralized (1,400 and 1,360 mg kg^{-1} soil, respectively) during the 16-wk period. There was no significant difference between middle and lower slope positions. In the timothy field, there was no significant difference in C mineralization between upper and middle slope positions (970 and 980 mg kg^{-1} soil, respectively), but the C mineralization from soils of the two positions were significantly lower than that of the lower and toe positions. The lower slope position had the highest amount of C mineralized (1,500 mg kg^{-1} soil) followed by the toe slope (1,220 mg kg^{-1} soil). There was a significant difference in C mineralization between lower and toe slope positions. The rate of C mineralization was greater in soils of the lower and toe slope positions compared with that of the upper and middle slope positions (Table 4.3).

The specific soil respiration rate during the 16-wk incubation was calculated as CO_2-C respired per day as a percentage of total soil C (Fig. 4.4). Specific soil respiration rate followed the opposite trend to that of the soil cumulative CO_2-C. In the mixed forage field, the trend of specific respiration rate was: upper ≥ middle > low. There was no significant difference between upper and middle slope positions in specific soil respiration rates but the lower slope position had significantly lower specific respiration rate. In the timothy field, the trend of specific respiration rate was middle ≥ upper > lower> toe. There was no significant difference between upper and middle slope positions in specific respiration rates. The lower and toe slope positions had significantly lower rate of respiration than that of the upper and middle slope positions. The toe slope position had significantly lower rate than that of the lower slope position.

There was no significant difference in the N mineralization between the two fields during the 16-wk incubation (Table 4.3 and Fig. 4.5). In the mixed forage field, there was no significant difference in cumulative N mineralized between upper and middle slope positions (73 and 78 mg kg^{-1} soil, respectively). The lower slope position had significantly higher cumulative N mineralized (96 mg kg^{-1} soil). In the timothy field, the

upper and middle positions had similar N mineralized (72 and 75 mg kg^{-1} soil, respectively). The lower and toe slope positions had significantly higher amount of N mineralized (101 and 109 mg kg^{-1} soil, respectively). There was no significant difference in the amount of cumulative N between lower and toe slope positions. The slopes for the cumulative N mineralization curves of soils from different slope positions increased from upper to toe slope positions (Table 4.3). The increase of the rate of N mineralization was consistent to the amount of N mineralized.

The specific soil N mineralization rate during the 16-wk incubation was calculated as mineralized N per day as a percentage of total soil N. Soil N mineralization rate decreased greatly and leveled off after wk 4 in soils from all slope positions in both fields (Fig. 4.5). Specific N mineralization rate followed the opposite trend to that of the net N mineralization in soil. In the mixed forage field, there was no significant difference in the specific N mineralization rate among soils from different slope positions. In the timothy field, the trend of specific N mineralization rate was: middle ≥ upper > lower > toe. There was no significant difference between upper and middle slope positions in specific N mineralization rates. The lower and toe slope positions had significantly lower rate of net mineralization than that of the upper and middle slope positions. The toe slope position had the lowest rate of all the slope positions.

There was no significant difference in the amount of mineralized ^{15}N between two fields (Fig. 4.6). In the mixed forage field, there was no significant difference in the mineralized ^{15}N among upper, middle and lower slope positions during the 16 wk (65, 66, and 64 μg kg^{-1} soil by wk 16, respectively). In the timothy field, the upper, middle and lower slope positions had no significant difference in the amount of ^{15}N mineralized (71, 58, and 71 μg kg^{-1} soil by wk 16, respectively). The lower slope position had significantly lower amount of mineralized ^{15}N than that of the other slope positions during the 16-wk incubation (39 μg kg^{-1} soil). The rate of net mineralized ^{15}N followed an order of upper = lower ≥ middle > toe slope positions.

The ratio of C to N mineralized during the incubation experiment did not differ significantly between the two fields (Table 4.3). The highest C to N mineralization ratio

occurred in the middle slope position of the mixed forage field (18) while the lowest occurred in the toe slope position of the timothy field (11).

Extractable P

Soil extractable P did not change much over the 16-wk incubation period (Fig. 4.7). The timothy field had significantly higher amount of extractable P than that of the mixed forage field. In the mixed forage field, the lower slope position had significantly lower amount of extractable P than that of the upper and middle slope positions. The upper and middle slope positions were not significantly different. In the timothy field, the rank of extractable P was middle > upper > lower > toe slope positions. The toe slope position had significantly lower amount of extractable P than rest of the slope positions. The same trend was found in the measurement of the field samples from growing season (Table 3.3, Chapter 3).

When the extractable P per day was expressed as a percentage of total soil P, the same trend as those in specific soil C and N mineralization rates held for the specific P mineralization rate. The lower slope position of the mixed forage field had significantly lower specific P mineralization rate than the upper and middle slope positions. There was no significant difference between upper and middle slope positions. In the timothy field, the toe slope position had significantly lower specific P mineralization rate than rest of the slope positions. There was no significant difference among the other three slope positions in specific P mineralization. Specific P mineralization decreased greatly from wk 6 and leveled off.

Soil specific respiration activity (qCO_2)

The specific soil respiration activity (qCO_2) was calculated as the CO_2 production per unit biomass and per unit time (Fig. 4.8). It is an index of metabolic activity of the soil biomass. The trend of qCO_2 is similar to that of the specific respiration rate (Fig. 4.4) and to that in the 10-day incubation study in Chapter 3 (refer to Table 3.4). In the mixed forage field, the upper and middle slope positions had no significant difference in qCO_2, and the lower position had significantly lower qCO_2. When qCO_2 was averaged across sampling days, it decrease in the order: upper (0.036 mg CO_2-C mg^{-1} biomass C day^{-1}) >

middle (0.034 mg CO_2-C mg^{-1} biomass C day^{-1}) > lower (0.023 mg CO_2-C mg^{-1} biomass C day^{-1}). In the timothy field, there was a significant difference in qCO_2 among all slope positions. The upper and middle slope position was not significantly different. The lower slope positions had significantly lower qCO_2. By averaging across sampling days, the qCO_2 tended to decrease in the order: middle (0.032 mg CO_2-C mg^{-1} biomass C day^{-1}) > upper (0.025 mg CO_2-C mg^{-1} biomass C day^{-1}) > lower (0.020 mg CO_2-C mg^{-1} biomass C day^{-1}) > toe (0.009 mg CO_2-C mg^{-1} biomass C day^{-1}). The toe slope position had significantly lower microbial metabolic quotient than any of the slope positions.

Indicators of microbial activity

The relationship of soil microbial biomass to the total soil C and N is shown in Table 4.4. Soil microbial biomass C and total C all increased from upper to lower slope positions in both fields. The amount of respired CO_2-C was higher in the lower slope positions, but the middle slope of the mixed forage field also had a high respiration (Table 4.4). Microbial C accounted for about 1.41 % of total C in the mixed forage field; while it accounted for about 1.10 % of total C in the timothy field. The lower slope position of the mixed forage field had the highest percentage of microbial C to total C (1.53%). Comparing the percentage of CO_2-C evolved per day to total C, however, the ratio decreased from upper to lower slope positions in both fields. The lower and toe slope positions had much lower percentage of total C respired (3.8×10^{-4} per day in the lower slope position of the mixed forage field; 2.5×10^{-4} and 1.0×10^{-4} per day in the lower and toe slope position of the timothy field, respectively). The same trend held for the ratio of CO_2-C to microbial C (2.0×10^{-2} and 9.0×10^{-3} per day in lower and toe slope positions of the timothy field, respectively). The middle slope position had lower biomass C content, but higher amount of C respiration (Table 4.4).

The N mineralization ratios followed the same trend as that of the C mineralization during the 16-wk incubation (Table 4.4). Soil microbial biomass N, soil total N and N mineralized in 16-wk from soils increased from upper to lower slope positions. The lower slope position of the timothy field had the highest percentage of microbial N to total N. However, the percentages of mineralized N to total N and of mineralized N to biomass N were much higher in upper and middle slope positions than that in the lower

and toe slope positions. The toe slope position had the lowest mineralized N based on the total N and biomass N pools.

Soil ^{15}N mineralization had a consistent trend to the C and N mineralization. Generally, the soils of lower and toe slope positions had higher microbial biomass ^{15}N and total ^{15}N (Table 4.4). However, the lowest amount of mineralized ^{15}N occurred in the toe followed by the middle slope position (39 and 58 $\mu g\ kg^{-1}$ soil in the toe and middle slope positions of the timothy field, respectively). The ratio of biomass ^{15}N to total ^{15}N was higher in the middle slope position of the mixed forage field (0.056%) while it was higher in the lower slope positions of the timothy field (0.096%). The ratio of mineralized ^{15}N to total ^{15}N and the ratio of mineralized ^{15}N to biomass ^{15}N were lower in the lower and toe slope positions than those in the upper and middle slope positions (Table 4.4).

N mineralization by both leaching and incubation methods

The N mineralization measured by the leaching method had the same trend as that measured by the 16-wk incubation method (Fig. 4.9). However, the magnitude of the amount of N mineralized was about 1.5 times greater in the leaching method than that obtained in the incubation method. For example, the upper slope position of the mixed forage field had 108 mg mineralized N kg^{-1} soil at the end of the 16-wk by the leaching method, while it had only 73 mg mineralized N kg^{-1} soil at the same sampling time by the laboratory incubation method.

DISCUSSION

Impact of topography on pool sizes

Carbon and N mineralization studies have been conducted in a wide variety of soils around the world, but relatively few studies have quantified the total soil C and N, respiration and N mineralization in soils from different slope positions along toposequences. Topography had a significant effect on the concentration of total soil C and N in the upper 0-12.5 cm soils from different slope positions. Soil total C and N increased from upper to lower slope positions. There were about 1.5 times more soil total C and 1.4 times more soil total N in soil from the lower slope position than soil in the

upper slope position of the mixed forage field. The toe slope position had about 5 times more soil total C and 4 times more soil total N than those of the upper slope position in the timothy field (Table 4.1). Soil C/N ratio widened from upper to toe slope positions indicating the difference in substrate quality of the soil organic matter. These trends in soil total organic matter by concentration were consistent with those in Chapter 2. Higher organic matter content correlated to higher total amount of soil C and N mineralization in the lower slope positions as demonstrated in this experiment and in previous two Chapters. Similar patterns of increasing soil total organic C and N were also found by studying soils from different landscape positions (Schimel et al. 1985; Novak and Bertsch 1991; Boehm and Anderson 1997).

Soils from the lower slope positions in both fields contained more total C, total N, microbial C, microbial N and ^{15}N, and had greater C_{mic}/C_{total}, N_{mic}/N_{total} $^{15}N_{mic}/^{15}N_{total}$ ratios than in soils from the upper and middle slope positions (Table 4.4). Our ratio of C_{mic}/C_{total} is well within the 0.27-7.0% range as reported in the literature (Anderson and Domsch 1980; Jenkinson and Ladd 1981; McGill et al. 1986). Soil microbial biomass C and N slightly decreased during the 16-wk incubation although there was no significant difference in microbial C and N with time (Fig. 4.1, 4.2). The soils in the lower slope position had higher microbial biomass population (Fig. 4.1, 4.2, 4.3; Table 4.2), which was sustained by a higher amount of soil organic matter in those positions. However, the soil from the toe slope position in the timothy field (Orthic Humic Gleysol) supported a lower amount of microbial biomass on a per unit of C or N basis, and the proportion of C and N respired was lower than the other slope positions.

Bauhus (1996) had observed a substantial decrease in soil microbial C and N in the mineral soil of the gap when comparing the C and N mineralization along a gap-stand gradient between forest floor material and mineral soil in a mature beech forest in Germany. The ratios of C_{mic}/C_{org} and N_{mic}/N_{org} decreased from the forest floor material to the mineral soil as the organic matter became more recalcitrant and humified. In the study of N cycling after burning and clear-cut logging on Luvisolic soils in Saskatchewan, Walley et al. (1995) found that the microbial biomass C was significantly higher in soils from shoulder positions at the burned site. The shoulder slope positions of

the native and clear-cut sites had higher microbial C than the foot slope position, although it was not statistically different. However, they found no significant effect of landscape position on the relative contribution of the microbial C to the total organic C pool. The microbial N to total N pool was significantly higher in the foot slope position of the clear-cut site.

Impact of topography on microbial activities

The soil C and N mineralization rates increased from upper to lower slope positions (Table 4.3), which corresponded to the cumulative amount of C and N mineralized. The difference in the rate of changes for soil microbial biomass in different slope positions may suggest that C and N may have been mineralized from different types of soil organic matter. Relatively low rate constants for soils suggest that C and N was slowly mineralized from recalcitrant organic matter (Zak et al. 1993). The net N mineralized after 40-wk laboratory incubation was 48 mg kg^{-1} soil from the surface soil samples in Gray Luvisols from the Breton plot (Juma 1993). This value could equal to the net N mineralization of soils from upper and middle slope positions in our study. Our value of net N mineralized was higher than his values (Table 4.3).

There is a strong correlation (0.99***) between net N mineralized and total CO_2-C evolved from soils obtained from all slope positions suggesting that total C and N mineralization process are intimately related. Only the toe slope position had significantly higher slope for the linear curve (data not shown), which suggests that, for each unit of C mineralized, more N is mineralized in the toe slope position than that of the other positions. Under conditions of net N mineralization, the soil C_{min} to N_{min} ratio is around 10. The C_{min} to N_{min} ratio in soils from different slope positions were greater than 10 (Table 4.3). This indicated that there was a greater availability of carbon substrates and/or a greater amount of N immobilization by soil microorganisms. The soil C and N mineralization rates were higher in the lower and toe slope position as shown by the greater zero-order mineralization rate constants for these soils (Table 4.3).

The ^{15}N mineralized showed the active soil microbial biomass. The soil of the toe slope position had the least soil microbial activities (Fig. 4.6). The soil total ^{15}N was the

highest in the toe and lower slope positions before the beginning of the experiment. However, the soil microbial biomass in the toe slope position was less active which mineralized less proportion of soil total ^{15}N. The ratios of $^{15}N_{min}/^{15}N_{total}$ and $^{15}N_{mic}/^{15}N_{total}$ decreased from upper to lower slope positions (Table 4.4), which support the concept that the soil microbial activity was much lower in the toe slope positions.

The extractable P decreased from upper to lower slope positions and the same with the extractable P to total P ratio. This trend was consistent with measurements made in the field samples in Chapter 3. Schimel et al. (1985) measured an extractable P availability increase and an available P as a percentage of total P increase from upper to lower slope positions. Our result showed a contrary trend to theirs. Although the size of the microbial biomass P pool was larger in the lower slope positions of our study, the microbial biomass activity might not be correspondingly higher, which could lead to less soil organic P mineralization in those soils.

The kinetics of soil organic matter mineralization along the toposequences was different. The indices of microbial activity measured as the ratios of CO_2-C/total C, mineral N/total N, and mineralized ^{15}N/total ^{15}N all decreased from upper to lower slope positions (Fig. 4.4, 4.5; Table 4.4). In contrast, the microbial biomass C, N and P increased along the toposequences. Although the size of microbial biomass and the C and N mineralization were larger in the lower slope positions, the microbial activities were not. The specific rate of C and N mineralization was much higher in the upper and middle slope position than in the lower and toe slope positions. The ratios of CO_2-C/total C, mineral N/total N also decreased over time indicating the recalcitrant nature of available substrates in the lower and toe slope positions. The observation was consistent to that in the previous two chapters. As the incubation time continued, the more resistant substrates were decomposed slowly.

Overall, the index of biological activities, the ratios of CO_2-C/C_{mic} (qCO_2), N_{min}/N_{mic} (qN) and $^{15}N_{min}/^{15}N_{mic}$ all decreased from upper to lower slope positions (Table 4.4). This is consistent with previous findings in Chapter 2 and 3. Ecosystem maturity and species diversity lead to lowering of qCO_2 values (Anderson and Domsch 1990; Fliessbach and

Mäder 1997). A lower metabolic N quotient would be associated with a higher immobilization capacity and lower mineralization rate over time (Smith et al. 1994). However, the differences in the kinetics of C and N mineralization along toposequences were mainly due to a greater proportion of less active soil microbial biomass in the lower and toe, especially in the toe slope positions, as demonstrated by the decreasing trend of qCO_2 and metabolic N quotient. The higher organic matter content in soils of lower and toe slope positions could provide more physical protection for microorganisms within soil aggregates. There are only a few studies in which the C and N mineralization along toposequences in arable soils was measured. Miller and Dick (1995) found the increase of microbial biomass C, the C_{mic}/C_{org} ratio and a decrease in qCO_2 in a soil management system with higher C inputs. Breland and Eltun (1999) also discovered a decreasing trend of qCO_2 with increasing of C and N mineralization in the forage than the arable crop soils during an incubation study. The qCO_2 also decreased over time in soils of our study (Fig. 4.8). This was consistent with the hypothesis that over the long term, the soil decomposer community became more efficient in their energy utilization shown by a decline of qCO_2 (Insam and Haselwandter 1989, Ross and Tate 1993).

The substrate quality of soil organic matter in the lower slope positions was different from the other slope positions. Higher plant production in the lower slope position (Table 3.1 in Chapter 3) lead to larger C inputs, therefore widened the C/N ratio of the soil organic matter. The ratio of C_{mic}/C_{total}, N_{mic}/N_{total} decreased with the stage of decay of substrates. Bauhus (1996), Ross and Tate (1993) and Wardle (1993) had used the C_{mic} to C_{org} as a measure of substrate quality. The soils from upper and middle slope positions had more active microbial biomass and turned over much faster than soils from lower slope positions. The soil C and N were less active in the lower slope positions than in the upper and middle slope positions, and less C and N were mineralized per unit of soil biomass in the lower slope positions.

When N mineralization was measured by leaching method, it was 1.5 times higher than measured by the incubation method on the same soil samples. Soil processing such as mixing with sand to increase aeration and leaching greatly increased the N mineralization. However, the trends of N mineralization from different soils were the

same between the two methods. Care must be taken when choosing the method of study. The result from leaching method can be used in our case since we are relatively comparing different C and N mineralization among slope positions.

Implications

Kinetic parameters have been used in this study to access the quality of soil organic matter in different slope positions of toposequences. These studies have shown that both the quantity and the quality of soil organic matter should be taken into account when studying the C and N mineralization along the toposequences.

Table 4.1. Soil total C and N contents in 0-12.5 cm depth in soils from different slope positions collected within the metal frames at different slope positions.

Slope position	Total C (mg kg^{-1})	Total N (mg kg^{-1})
	Mixed forage field	
Upper	22,700 a	2,120 a
Middle	27,000 a	2,450 a
Lower	33,600 b	2,950 b
	Timothy field	
Upper	27,600 a	2,390 a
Middle	26,700 a	2,260 a
Lower	55,600 b	4,300 b
Toe	132,300 c	9,270 c

	Summary of ANOVA		
Source of variation	d.f.	Total C	Total N
Field	1	NS	NS
Position	3	***	***
Field × Position	3	NS	NS

For each column, values marked with the same letter are not significantly different ($P<0.05$)
*, **, *** $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively; NS, not significant.

Table 4.2. Initial and final soil microbial biomass P in 0-12.5 cm depth in soils from different slope positions of the two fields during 16-wk incubation.

Slope position	Microbial biomass P (mg kg^{-1}) Initial	Final
	Mixed forage field	
Upper	29 aA	33 aA
Middle	31 aA	28 aA
Lower	36 aA	48 aB
	Timothy field	
Upper	49 aA	34 aA
Middle	26 aA	35 aA
Lower	33 aA	87 aB
Toe	76 bB	88 bB

Source of variation	Summary of ANOVA d.f.	Microbial biomass P
Time	1	NS
Field	1	NS
Position	3	***
Time × Field	1	NS
Time × Position	3	NS
Field × Position	3	NS
Time x Field x Position	3	NS

For each row and column, values of each variable marked with the same letter are not significantly different (P<0.05); Uppercase letters are comparisons within sampling dates for slope position, lowercase letters are comparisons among time, field and slope positions.
*, **, *** $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively; NS, not significant.

Table 4.3. Sums of mineralized C and N, ratios of mineralized C and N, and zero-order C and N mineralization rate constants in soil samples in 0-12.5 cm depth from different slope positions incubated over 16-wk.

Slope position	ΣCO_2-C mg kg^{-1}	ΣN_{min} mg kg^{-1}	C_{min} / N_{min}	C gradient mg kg^{-1} soil day^{-1}	N gradient mg kg^{-1} soil day^{-1}
		Mixed forage field			
Upper	1,130 a	73 a	15 a	182 a	4.4 a
Middle	1,400 b	78 a	18 b	223 b	4.6 a
Lower	1,360 b	96 b	14 a	219 b	5.6 b
		Timothy field			
Upper	970 c	72 a	14 a	157 c	4.2 a
Middle	980 c	75 a	13 a	160 c	4.1 a
Lower	1,500 d	101 b	15 a	243 d	5.7 b
Toe	1,220 e	109 b	11 c	193 e	6.1 b

Summary of ANOVA

Source of Variation	d.f.	ΣCO_2-C	ΣN_{min}	C_{min} / N_{min}	C gradient	N gradient
Time	5	***	***	NS		
Field	1	NS	NS	NS	NS	NS
Position (field)	5	*	***	**	**	***
Time × Field	5					
Field x Position	5	NS	NS	NS	NS	NS
Position x Time	25	***	NS	NS		
Time x Field x Position	25	NS	NS	NS		

For each column, values marked with the same letter are not significantly different ($P<0.05$)
*, **, *** $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively; NS, not significant.

Table 4.4. Soil microbial biomass, total, and mineralized C and N relationships among different slope positions by the end of the 16-wk incubation experiment.

Slope position	Microbial C (mg kg^{-1})	Total C (mg kg^{-1})	CO_2-C (mg kg^{-1})	Microbial C/Total C (%)	CO_2-C day^{-1}/ Total C	CO_2-C day^{-1}/ Microbial C
			Mixed forage field			
Upper	337	22 700	1 130	1.48	4.5×10^{-4}	2.9×10^{-2}
Middle	396	27 000	1 400	1.47	4.7×10^{-4}	3.1×10^{-2}
Lower	592	33 600	1 360	1.76	3.8×10^{-4}	2.0×10^{-2}
			Timothy field			
Upper	332	27 600	970	1.20	3.3×10^{-4}	2.6×10^{-2}
Middle	296	26 700	980	1.10	3.3×10^{-4}	2.9×10^{-2}
Lower	755	55 600	1 500	1.36	2.5×10^{-4}	1.7×10^{-2}
Toe	1 400	132 300	1 220	1.06	1.0×10^{-4}	7.7×10^{-3}
	Microbial N (mg kg^{-1})	Total N (mg kg^{-1})	Mineralized N (mg kg^{-1})	Microbial N/ Total N x 100 (%)	Mineralized N day^{-1}/ Total N	MineralizedN day^{-1}/ Microbial N
			Mixed forage field			
Upper	41	2120	73	1.93	3.1×10^{-4}	1.6×10^{-2}
Middle	55	2450	78	2.25	2.8×10^{-4}	1.3×10^{-2}
Lower	63	2950	97	2.14	2.9×10^{-4}	1.4×10^{-2}
			Timothy field			
Upper	59	2390	72	2.47	2.7×10^{-4}	1.1×10^{-2}
Middle	35	2260	75	1.55	3.0×10^{-4}	1.9×10^{-2}
Lower	132	4300	101	3.07	2.1×10^{-4}	6.8×10^{-3}
Toe	172	9270	109	1.86	1.0×10^{-4}	5.7×10^{-3}
	Microbial ^{15}N ($\mu g\ kg^{-1}$)	Total ^{15}N ($\mu g\ kg^{-1}$)	Mineralized ^{15}N ($\mu g\ kg^{-1}$)	Microbial ^{15}N / Total ^{15}N (%)	Mineralized ^{15}N day^{-1}/ Total ^{15}N	Mineralized ^{15}N day^{-1}/ Microbial ^{15}N
			Mixed forage field			
Upper	33	39 500	65	0.083	1.78×10^{-5}	1.8×10^{-2}
Middle	43	44 600	66	0.096	1.67×10^{-5}	1.4×10^{-2}
Lower	38	44 800	64	0.085	1.67×10^{-5}	1.5×10^{-2}
			Timothy field			
Upper	49	49 100	71	0.099	1.34×10^{-5}	1.3×10^{-2}
Middle	43	32 100	58	0.134	2.14×10^{-5}	1.2×10^{-2}
Lower	90	51 100	71	0.176	1.70×10^{-5}	7.0×10^{-3}
Toe	77	62 000	39	0.124	1.34×10^{-5}	4.5×10^{-3}

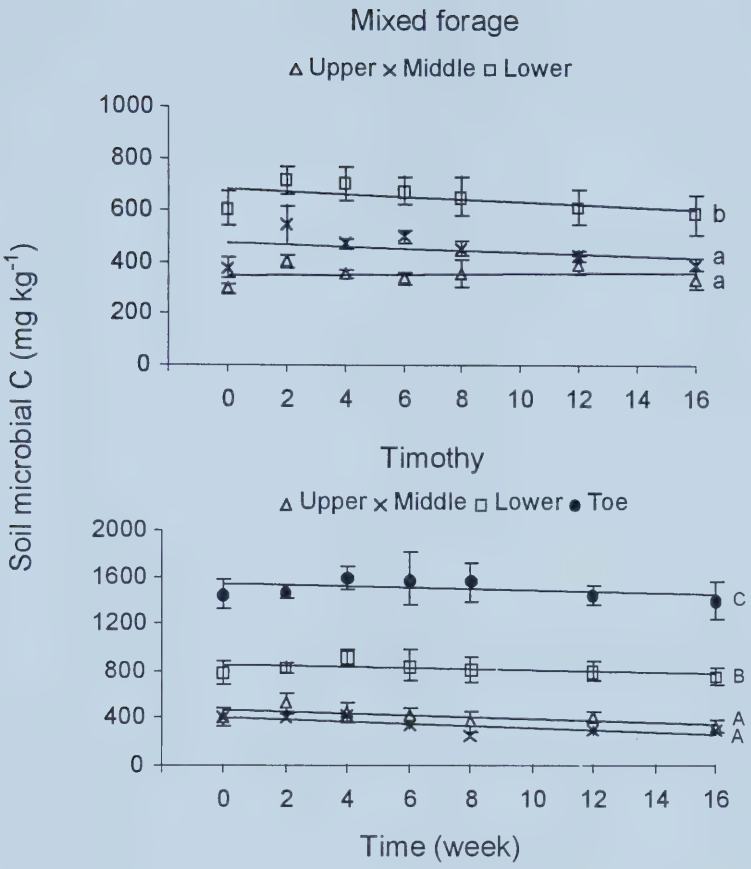

Fig. 4.1. Soil microbial biomass C from different soils during the 16-wk incubation; LSD = 301. Lines carrying the same letter are not significantly different ($P < 0.05$).

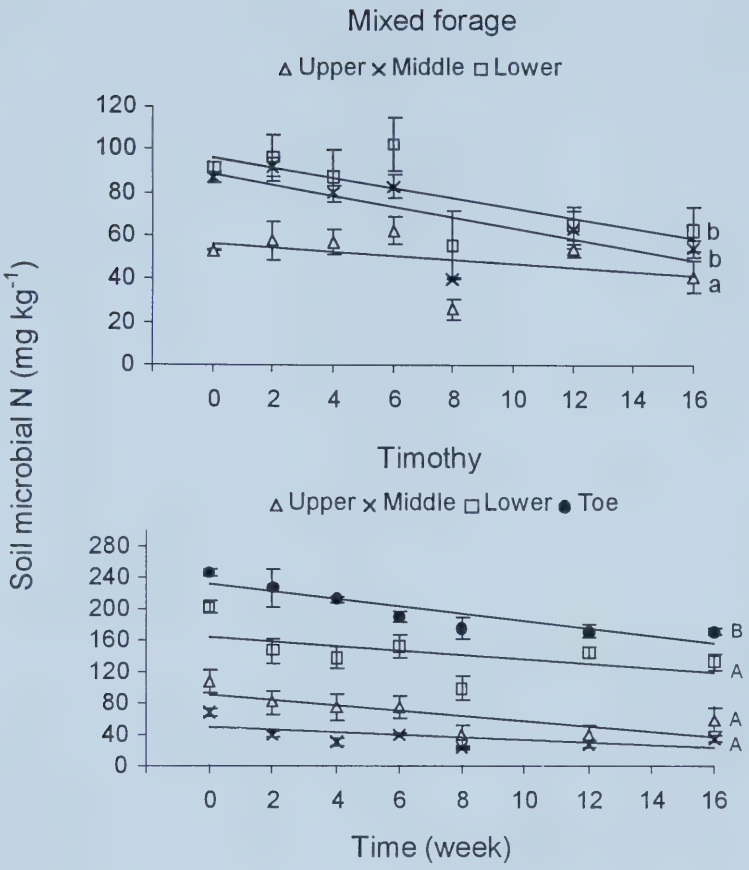

Fig. 4.2. Soil microbial biomass N from different soils during the 16-wk incubation; LSD = 29. Lines carrying the same letter are not significantly different ($P < 0.05$).

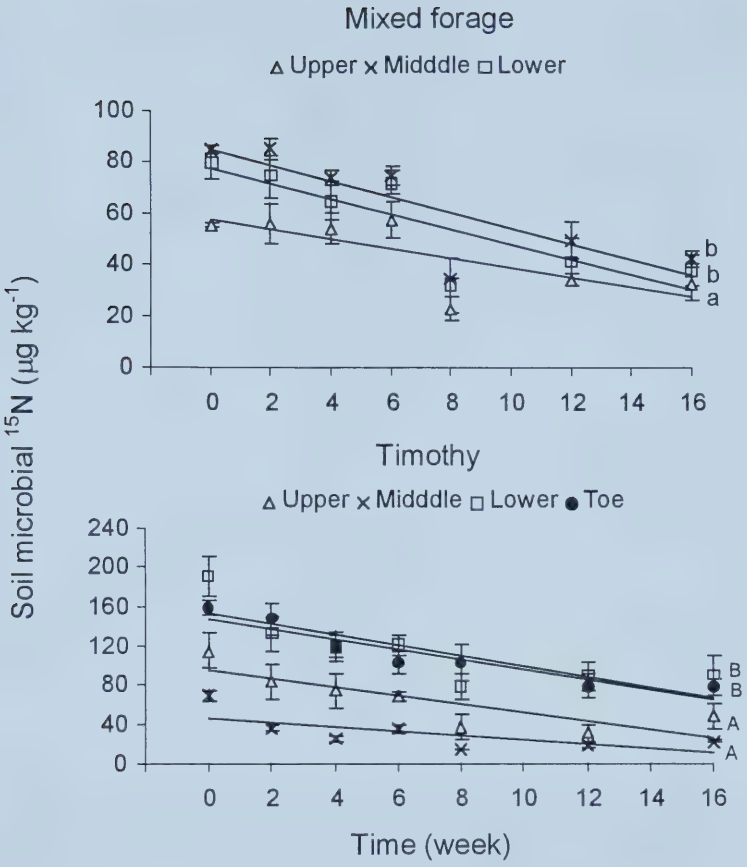

Fig. 4.3. Microbial biomass ^{15}N in soil samples from different slope positions during the 16-wk laboratory incubation; LSD = 14. Lines carrying the same letter are not significantly different ($P < 0.05$).

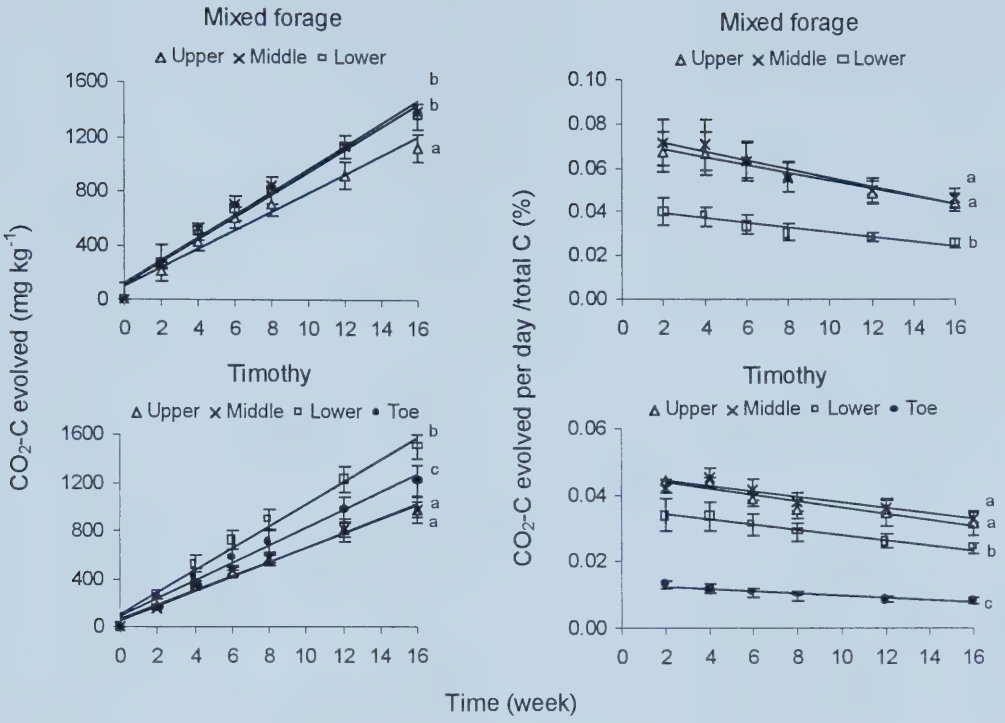

Fig. 4.4. Soil cumulative C evolved and percent total C mineralized (cumulative C evolved/number of incubation days/total C x 100) in soils from different slope positions in the mixed forage and timothy fields during the 16-wk laboratory incubation; LSD: cumulative CO_2-C = 221; C mineralization = 0.026. Lines carrying the same letter are not significantly different ($P < 0.05$).

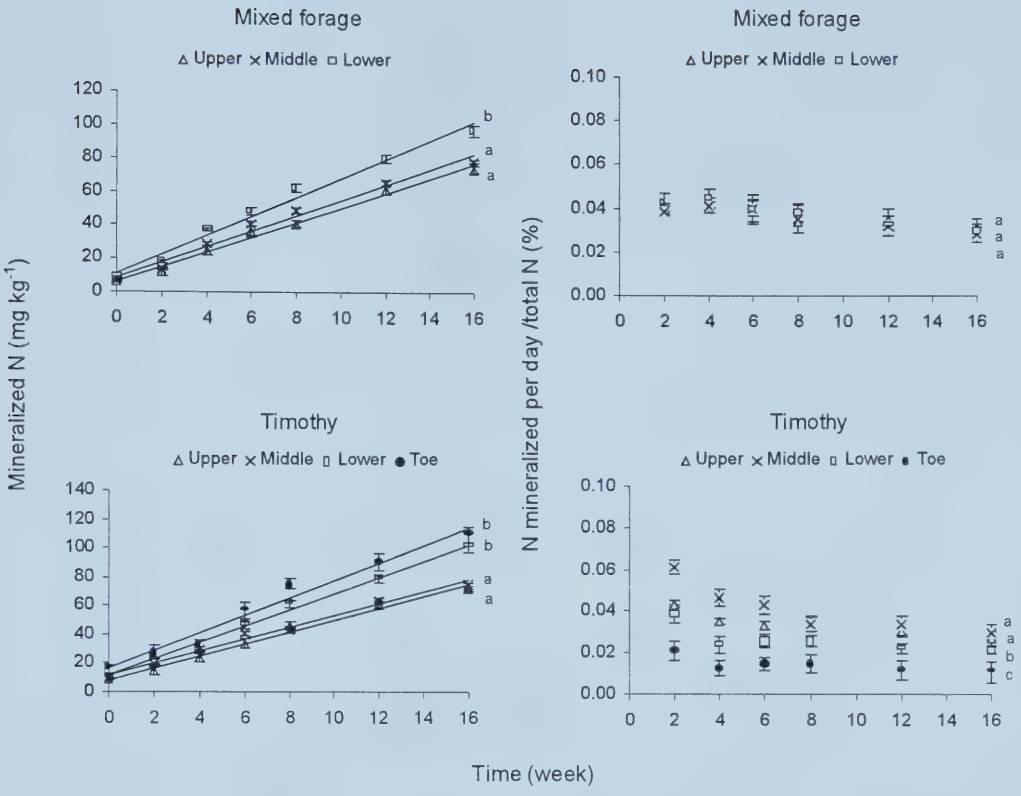

Fig. 4.5. Soil cumulative N evolved in soils from different slope positions in the mixed forage and timothy fields during the 16-wk laboratory incubation; LSD = 39. Lines carrying the same letter are not significantly different ($P < 0.05$).

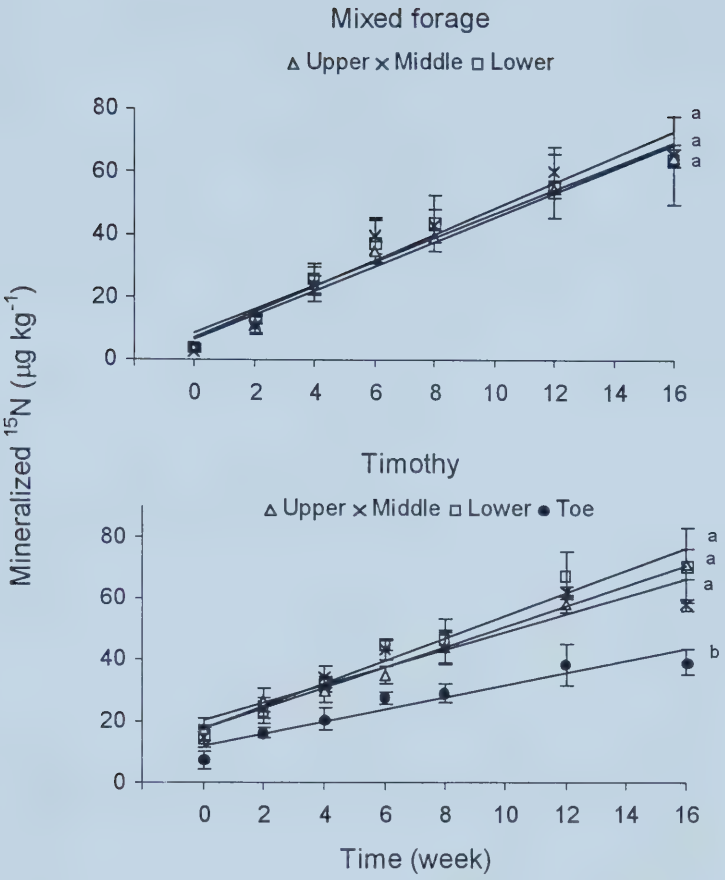

Fig. 4.6. The amount of ^{15}N mineralized from samples from different slope positions during the 16-wk laboratory incubation; LSD = 6.7. Lines carrying the same letter are not significantly different ($P < 0.05$).

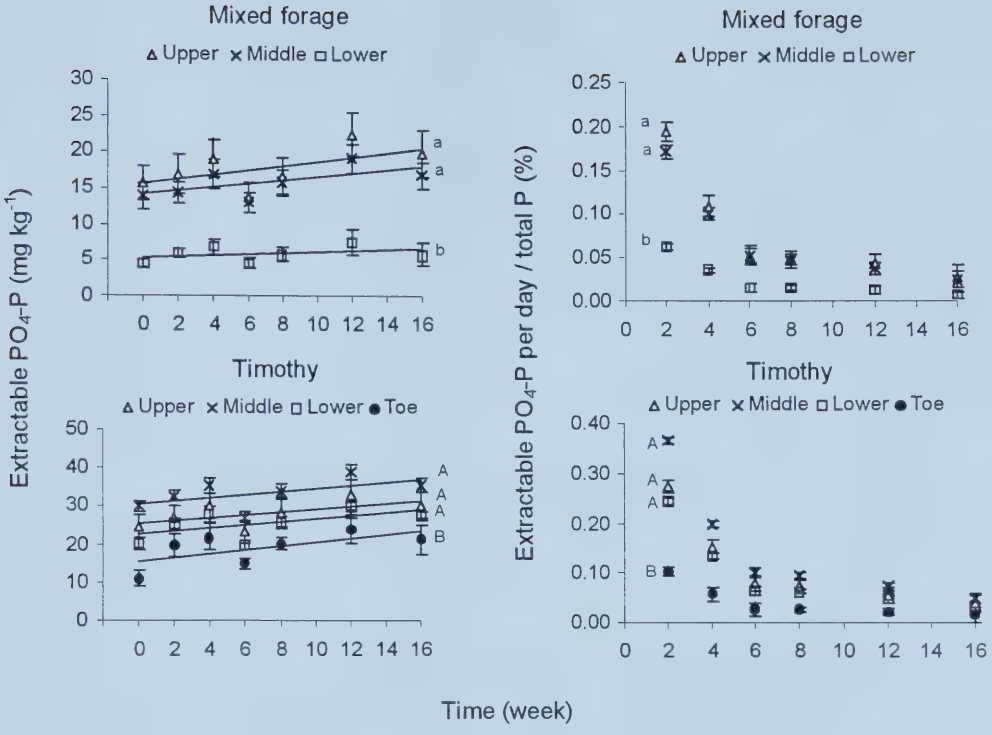

Fig. 4.7. Extractable P from soils of different slope positions from two fields during 16-wk laboratory incubation; LSD: Extractable P = 9.6; Total P mineralized = 0.12. Lines carrying the same letter are not significantly different ($P < 0.05$).

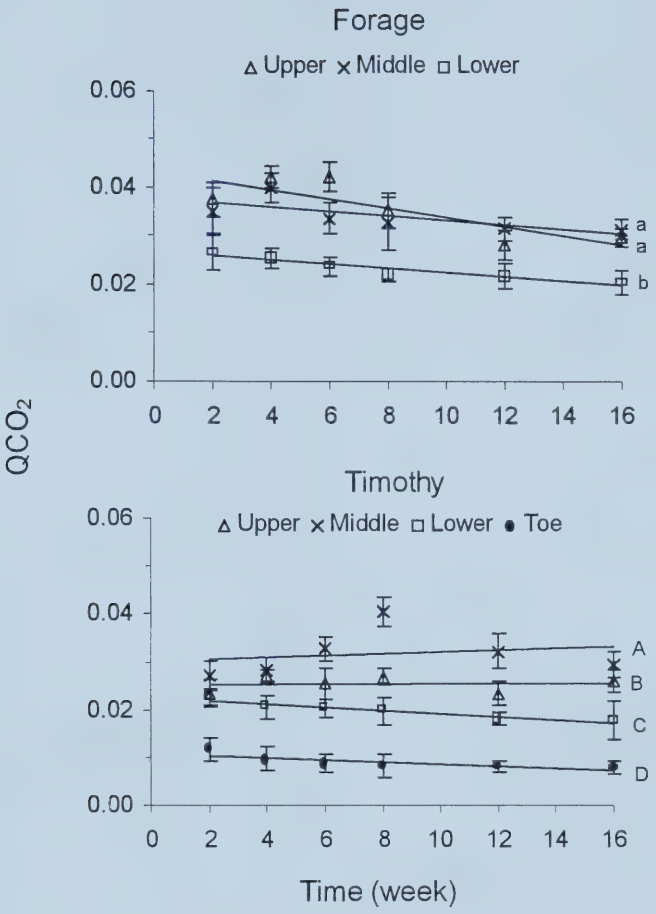

Fig. 4.8. Soil respiration activity qCO_2 [CO_2-C (mg kg^{-1} soil day^{-1}) / biomass C (mg kg^{-1} soil)] in soils from two fields during 16-wk incubation; LSD = 0.13. Lines carrying the same letter are not significantly different ($P < 0.05$).

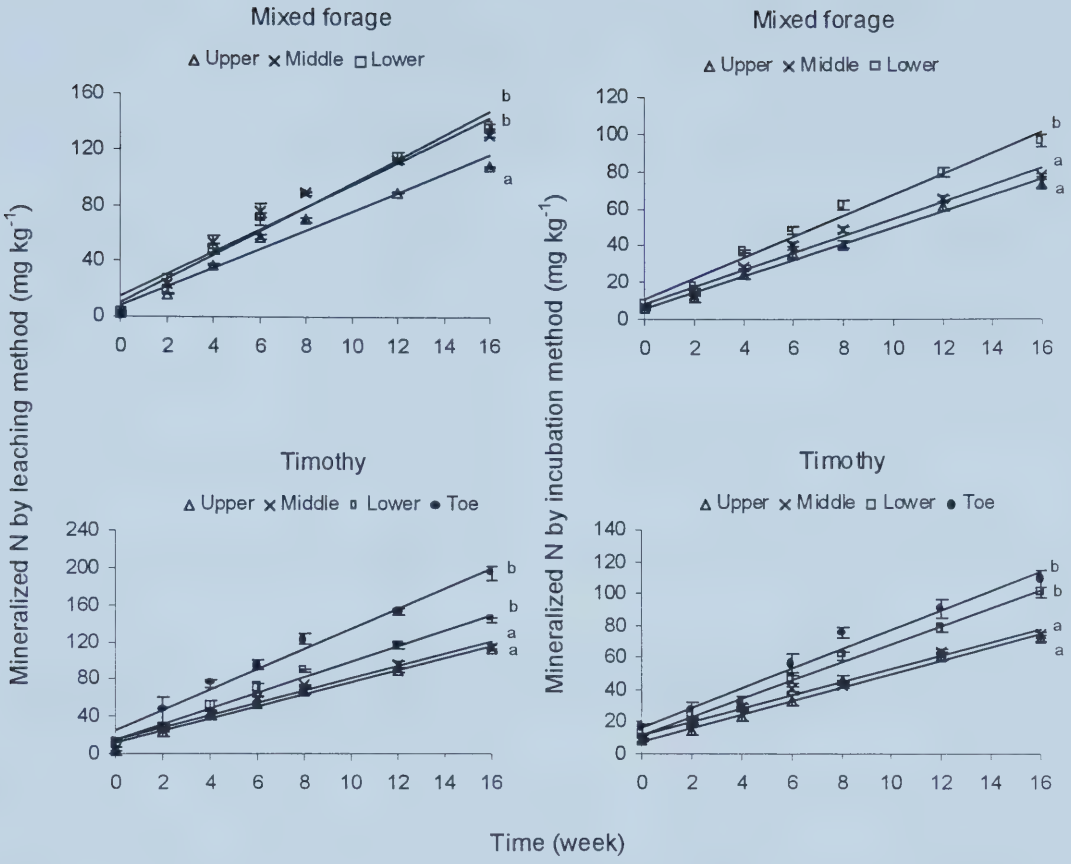

Fig. 4.9. Comparison of total N mineralized during the 16-wk by both leaching and incubation methods. Lines carrying the same letter are not significantly different ($P < 0.05$).

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Chapter 5. Summary, Synthesis and Implications

Crop yields, soil organic matter trends and soil C and N mineralization studies had been studied on the long-term plots in Breton, Alberta. The Breton plots, established in 1930, have yielded information on soil properties and plant biomass production in a 2-yr wheat-fallow and a 5-yr cereal forage long term crop rotations (Izaurralde et al. 2001; Juma et al. 1997; Robertson 1990). The Breton plots are located on level to gently sloping land, therefore these plots have not been used to study the impact of topography on soil organic matter dynamics. The purpose of this study was to investigate the soil properties, soil water and temperature regimes, and C and N mineralization in soils located in different positions of toposequences in a farm adjacent to the Breton plots. Our work focused on the dynamics of soil organic matter changes and kinetics of soil C and N mineralization along toposequences in two fields adjacent to the Breton plots.

MAJOR FINDINGS

In Chapter 2, the amount of total C, N and P and light fraction in the fields was measured. Soil organic matter was found to increase from upper to lower slope positions along the toposequences. The kinetics of soil organic matter mineralization in the 10 wk laboratory incubation study showed that the quality of organic matter was different along the toposequences. The absolute amount of soil microbial biomass, soil C and N mineralization increased from upper to lower slope positions. However, the coefficients of specific mineralization rates of soils from different slope positions were significantly different. The soil microbial biomass activity was less and a smaller proportion of organic matter was mineralized in the lower slope positions. Soil organic matter in the lower slope positions may be more stabilized compared to that of the upper slope positions. Schimel et al. (1985) and Ragbubanshi (1992) also discovered a decreasing trend of proportion of organic matter mineralization along toposequences in their studies of C and N mineralization of soils in catenas. These findings suggest that different specific organic matter mineralization rate constants should be applied when studying the soil organic matter decomposition within toposequences.

In Chapter 3, field measurements of plant production, soil microbial biomass over growing season and soil moisture and temperature *in situ* for over a year were conducted in order to relate the differences in the quantity and the quality of soil organic matter in toposequences. The *in situ* monitoring of soil moisture and temperature revealed that the lower slope position had significantly higher amount of water content, lower temperature and warmed up much later in the spring thaw time. Higher moisture and lower temperature could result in soil organic matter accumulation in the lower slope positions compared with the better-drained higher landscape elements (Baldock et al. 2000; Stevenson 1994). Microbial activity is temperature dependent and a shift in the microbial community composition occurs at higher temperatures so that the microorganisms can metabolize substrates that are not used by microbial communities at lower temperatures (Zak et al. 1999; MacDonald et al. 1995).

Soil microbial biomass did not change over the growing season, but it was significantly higher in the lower slope positions. The proportion of soil total organic carbon mineralized decreased from upper to lower slope positions during the growing season, which further supported the results in Chapter 2, in which the quality of soil organic matter was different along the toposequences in the two fields. The soil microbial biomass was less active in the lower slope positions. The plant yield increased from upper to lower slope positions only in the timothy field. As 1999 was a wet year, the plant yield differences in the toposequences could have been minimized. The labile NO_3-N was significantly lower in the 7.5-15 cm soil of the toe slope position, suggesting that denitrification may be occurring in the soils due to the high water table.

To further investigate the kinetics of soil organic matter mineralization in different slope positions in toposequences, ^{15}N field-labeled soil samples were used in a 16 wk laboratory incubation described in Chapter 4. The data from this laboratory incubation experiment further supported observations made in Chapter 2 and 3. The specific rate of soil organic matter mineralization decreased from upper to lower slope positions along the toposequences. Although the absolute pool size of soil microbial biomass was greater in the lower slope positions, the kinetic parameters of microbial activity (^{15}N mineralized, soil C and N metabolic quotients and specific rates of C and N mineralization) were

lower compared to the upper and middle slope positions. From these observations, I concluded that the quality of the soil organic matter substrates in lower and toe slope positions was different from that in the upper and middle slope positions.

SYNTHESIS

The kinetic data of the C and N mineralization from the three experiments (Chapter 2, 3 and 4) are presented in Table 5.1 and 5.2. There was a distinct slope position difference in all indicators of soil microbial activity. The lower and toe slope position had significantly lower proportion of C and N mineralized, and lower C and N metabolic quotients (Table 5.1, 5.2). The soil microbial activity was lower in the lower slope positions compared to that of the upper slope positions. This suggests that soil organic matter in the lower slope positions contains more resistant materials, which turnover slowly. The C and N mineralization ratios, as indicators of substrate quality in soils, have been used by Bauhus (1996), Ross and Tate (1993) and Wardle (1993). They observed the decline of C_{mic}-to-C_{org} ratios from fresh litter to humified material. Concentrations of available C control relative amounts of microbial biomass. The C_{mic}-to-C_{org} ratio is thus a measure of substrate quality (Bauhus 1996). Although the soil organic matter in the upper slope positions supported smaller soil microbial biomass, the relative mineralization rates were much higher in these soils compared to those from the lower slope positions. Therefore, I concluded that the soil organic matter in the upper slope position had a higher turnover rate than that in the lower slope positions.

The ratios of CO_2-C evolved to total C decreased when compared among the 10-day, 70-day and 112-day incubation periods. The ratio of CO_2-C/total C was much lower in the 112-day incubation than the 10-day because the labile soil organic matter is mineralized first in the initial portions of the incubation studies. The 70-day incubation yielded the intermediate ratios and the 112-day incubation yielded the lowest ratios, which indicated that more resistant materials were mineralized later. The soil metabolic quotients also decreased from 10-day to 112-day incubation as the availability of labile carbon source decreases per unit of biomass C, the proportion of active biomass decreases. Moreover, the presence of less labile substrate could induce changes in soil microbial biomass composition or its physiological state, resulting in a lower production

of CO_2-C per unit of biomass C (Jans-Hamermeister 1996). The low metabolic quotient might indicate the low-level steady-state of microbial activity as suggested by Anderson and Domsch (1985; 1989) and Beyer et al. (1999).

The ratio of N mineralized to total N was lowest in the 112-day incubation and showed the same trend for C mineralization. Ratio of microbial N to total N also decreased from 10-day to 112-day incubation. However mineralized N to microbial N was higher in the 112-day incubation. These showed that the soil microbial N deceased as an indication of decreasing microbial activity as the duration of incubation increased.

IMPLICATIONS

In assessing the soil organic matter dynamic at a toposequence or a landscape level, not only the quantity of organic matter but also its quality should be addressed. Different coefficients of mineralization need to be applied to quantify soil organic matter mineralization. The knowledge of the spatial variability of soil organic matter mineralization in the toposequences can be used to development better estimates of C and N sequestration and greenhouse gas production. The understanding of the spatial scale variability of microbial processes is also required for the development of soil organic matter and management models.

FUTURE STUDIES

A number of areas still need to be examined:

1) How different are the humic substances in soil organic matter from different slope positions? Does this difference in complexity lead to lower rate of mineralization as this study and others suggest? Novak and Bertsch (1991) found higher organic C content, O-alkyl structured compounds, humic acids and HA/FA ratios in the bottomland soils. They suggested that topography might modify the formation and nature of humic substances in SOM by influencing the drainage, vegetation and litter quality.

2) Is there a quantitative relationship between N losses and slope positions in the field? The high moisture content and fluctuating water table in the lower slope

positions during the wet season may lead to denitrification and leaching process in fields. Pennock et al. (1992) had found landscape-scale variations in denitrification from an agricultural ecosystem in a Brown Chernozemic soil in southern Saskatchewan. The denitrification process was highly correlated with soil volumetric water content and redox potential.

3) Is it possible to conduct *in situ* measurement of soil microbial respiration and nitrogen mineralization in different slope positions along the toposequences? What are the actual amounts of CO_2-C evolved and N mineralized in soils from different slope positions during the growing season? Laboratory incubation methods provide optimum conditions for organic matter mineralization and may over- or under- estimates the field dynamics. Therefore *in situ* measurements are needed to correlate field values with the laboratory data.

Table 5.1. Comparison of soil organic matter C mineralization kinetics in surface soil depth among different experiments.

Slope Position	10-day (0-7.5 cm)	70-day (0-7.5 cm)	112-day (0-12.5 cm)
	Ratio of CO_2-C evolved per day / total C		
	Mixed forage field		
Upper	1.1×10^{-3}	6.0×10^{-4}	4.5×10^{-4}
Middle	9.5×10^{-4}	5.1×10^{-4}	4.7×10^{-4}
Lower	6.7×10^{-4}	3.2×10^{-4}	3.8×10^{-4}
	Timothy field		
Upper	5.9×10^{-4}	4.3×10^{-4}	3.3×10^{-4}
Middle	6.2×10^{-4}	5.0×10^{-4}	3.3×10^{-4}
Lower	3.8×10^{-4}	3.0×10^{-4}	2.5×10^{-4}
Toe	4.1×10^{-4}	1.4×10^{-4}	1.0×10^{-4}
	Ratio of microbial C / total C (%)		
	Mixed forage field		
Upper	1.08	1.38	1.48
Middle	1.07	1.40	1.47
Lower	1.14	1.21	1.76
	Timothy field		
Upper	0.94	1.07	1.20
Middle	0.95	1.09	1.10
Lower	0.80	0.83	1.36
Toe	0.71	0.52	1.06
	CO_2-C / microbial C		
	Mixed forage field		
Upper	1.0×10^{-1}	4.4×10^{-2}	2.9×10^{-2}
Middle	6.0×10^{-2}	3.6×10^{-2}	3.1×10^{-2}
Lower	5.9×10^{-2}	2.9×10^{-2}	2.0×10^{-2}
	Timothy field		
Upper	6.3×10^{-2}	4.1×10^{-2}	2.6×10^{-2}
Middle	6.5×10^{-2}	4.6×10^{-2}	2.9×10^{-2}
Lower	4.8×10^{-2}	4.6×10^{-2}	1.7×10^{-2}
Toe	5.8×10^{-2}	2.9×10^{-2}	7.7×10^{-3}

Table 5.2. Comparison of soil organic matter N mineralization kinetics in surface soil depth among different experiments.

Slope Position	10-day (0-7.5 cm)	70-day (0-7.5 cm)	112-day (0-12.5 cm)
Ratio of N mineralized per day / total N			
	Mixed forage field		
Upper	4.0×10^{-4}	4.5×10^{-4}	3.1×10^{-4}
Middle	3.8×10^{-4}	4.0×10^{-4}	2.8×10^{-4}
Lower	2.7×10^{-4}	3.7×10^{-4}	2.9×10^{-4}
	Timothy field		
Upper	4.4×10^{-4}	4.2×10^{-4}	2.7×10^{-4}
Middle	4.9×10^{-4}	4.8×10^{-4}	3.0×10^{-4}
Lower	3.8×10^{-4}	4.2×10^{-4}	2.1×10^{-4}
Toe	2.5×10^{-4}	2.8×10^{-4}	1.0×10^{-4}
Ratio of microbial N / total N (%)			
	Mixed forage field		
Upper	2.40	N/A	1.93
Middle	2.23	N/A	2.25
Lower	1.93	N/A	2.14
	Timothy field		
Upper	1.85	N/A	2.47
Middle	1.79	N/A	1.55
Lower	1.61	N/A	3.07
Toe	1.67	N/A	1.86
Mineralized N / microbial N			
	Forage field		
Upper	2.1×10^{-2}	N/A	1.6×10^{-2}
Middle	1.3×10^{-2}	N/A	1.3×10^{-2}
Lower	9.0×10^{-3}	N/A	1.4×10^{-2}
	Timothy field		
Upper	2.4×10^{-2}	N/A	1.1×10^{-2}
Middle	2.7×10^{-2}	N/A	1.9×10^{-2}
Lower	2.1×10^{-2}	N/A	6.8×10^{-3}
Toe	1.5×10^{-2}	N/A	5.7×10^{-3}

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